

*THE INFLUENCE OF GEOLOGICAL, GENETIC AND ECONOMIC
FACTORS ON THE ORE RESERVE ESTIMATION OF
KWAGGASHOEK EAST IRON ORE DEPOSIT*

THESIS

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ABSTRACT

Tectonics plays an important role in the genesis and subsequent mining development of the Kwaggashoek East ore body. Lithological key units control the effectiveness of the ore forming processes, affecting the in situ ore reserve.

The Kwaggashoek East deposit is the product of primary and secondary processes. A genetic model focussed on the source, migration and deposition of iron suggests a possible original source of iron as the product of very dilute hydrothermal input into deep ocean waters, with subsequent migration through structural conduits. Supergene processes account for the upgrading of the ore and the phosphorus redistribution. A good correlation between samples in a preliminary geostatistical study reflects the effectiveness of this process in the high grade ore zone.

A broad overview of the economic issues which affect the commercialization of iron, indicates a balanced supply-demand situation for the five next years.

The reserve estimation procedure requires accurate scientific terminology and appropriate methodology. Documentation is essential and should be detailed enough to allow for future reassessment. The results of three estimation methods in Kwaggashoek East differ by less than 5%. The accuracy of the final results depends more on geological interpretation and assumptions than on the method applied.

Although optimization of grade and tonnage in the Kwaggashoek East deposit seems to be met with the actual cut-off grade used in the Thabazimbi mine district, the grade-quality concept introduced in this thesis indicates a decrease in the estimated reserves for the deposit.

CONTENTS

ABSTRACT	
I INTRODUCTION	1
SECTION A - GEOLOGY AND GENESIS	
II GEOLOGICAL SETTINGS	3
2.1 Regional Geology	3
2.2 Local Geology	9
2.2.1 Lithology	10
The footwall dolomite	10
The footwall shale	11
The banded iron formation	13
The mineralized body	14
The talc-hematite and carbonate-hematite rocks	15
2.3 Geochemistry	16
2.3.1 Distribution of iron and the main deleterious elements within the mineralized body.	17
Iron	19
Silica	21
Aluminium	21
Phosphorus	22
Manganese	25
Potassium	27
III GENETIC MODEL	28
3.1 General concepts	28
3.2 Primary processes	29
Source of iron	34
Conduits	35
Iron precipitation	38
3.3 Secondary processes	39
Metamorphism	40
Supergene enrichment	42
IV CONCLUSIONS	45

SECTION B - ECONOMICS AND ORE RESERVES

V ECONOMIC INTRODUCTION	47
5.1 Commodity analysis	49
Resources	50
Supply	51
Demand and Uses	55
Prices	58
Mine grade and reserves	60
Commodity analysis Conclusions	61
VI ORE RESERVE ESTIMATION	62
6.1 Introduction	62
6.2 Ore definition	63
The Thabazimbi concept of ore	66
6.3 Reserve definition and different categories	67
6.4 Sampling	69
6.5 Grade	73
Natural grade	75
Preliminary cut-off grade	75
In situ grade	76
6.6 Tonnage	78
Specific gravity	80
6.7 Estimation methods	80
Basic assumptions	83
Cross-sections methods	84
Statistical methods	86
Geostatistics	89
6.8 Grade-tonnage curve	90
6.9 The negative impact of phosphorous in the Kwaggashoek reserve estimation	92
VII GENERAL CONCLUSIONS	98
ACKNOWLEDGEMENTS	101
REFERENCES	102
APPENDICES	

FIGURES

Fig. 2.1	Geologic map showing distribution of the Transvaal Sequence in the Transvaal and Griqualand West areas and their associated iron-formations.	4
Fig. 2.2	Schematic lithostratigraphic column of the Transvaal Sequence in the Thabazimbi area.	5
Fig. 2.3	Geological and Bouguer anomaly contour map of the Transvaal and Bushveld Complex within the Transvaal Basin.	8
Fig. 2.4	Geological sketch map of the Thabazimbi mining area.	10
Fig. 2.5	Geological Section of the Kwaggashoek East deposit. Section K070 view from the east.	12
Fig. 2.6	Different population in relation to iron content in Kwaggashoek East iron ore.	19
Fig. 2.7	Fe distribution in BIF, Kwaggashoek East iron deposit.	20
Fig. 2.8	Distribution of iron and the main deleterious elements in the mineralized body (Fe>45%).	23
Fig. 2.9	Distribution of iron and the main deleterious elements in high grade ore (Fe 60%-70%).	24
Fig. 3.1	Distribution of early Proterozoic basins with major iron-manganeses formations on a continental reconstruction prior to Proterozoic supercontinent aggregation.	30
Fig. 3.2	Tectonic environment for deposition of iron formation.	33
Fig. 3.3	Model for deposition of iron and manganese from upwelling anoxic waters.	39
Fig. 3.4	Geological section (K0-64) of Kwaggashoek East deposit, showing the dolerite dyke as a barrier for the supergene enrichment.	43
Fig. 5.1	Some questions that arise in assessing an ore reserve estimation and different disciplines related to them.	47
Fig. 5.2	World reserves of iron ore.	50
Fig. 5.3	World iron ore production.	51
Fig. 5.4	World Steel Production.	56

Fig. 5.5	Iron ore prices in South Africa R/t.	58
Fig. 5.6	Prices agreed by producers who sell to Japan.	59
Fig. 6.1	AIMM/AMIC classification of identified mineral resources and reserves.	68
Fig. 6.2	Proportion of ore mineral versus homogeneity.	71
Fig. 6.3	Schematic diagram depicting some of the senses in which grade is used through the first steps in the development of a mineral deposit.	74
Fig. 6.4	Geological section of Kwaggashoek East showing three zones of in situ ore grade quality.	77
Fig. 6.5	Estimation methods as one of the major components of ore reserve estimation.	81
Fig. 6.6	Cross-Section Methods - Standard and Linear.	85
Fig. 6.7	Preliminary Grade-tonnage curve for Kwaggashoek East deposit.	91
Fig. 6.8	Grade-tonnage curve for different grade quality cut-off.	96

PLATES

Plate 2.1	Typical brecciated ore: primary hematite fragments (a), set within a secondary hematite matrix (b).	14
Plate 2.2	Carbonate-Hematite rock from Kwaggashoek East deposit.	16
Plate 3.1	Contact between the foot-wall shale and the brecciated ore body showing the absence of brecciation in the underlying shale.	37

TABLES

Table 2.1	Thabazimbi ore specifications for final product.	17
Table 2.2	Average values of iron and some deleterious elements at Kwaggashoek East deposit in three kinds of populations.	18
Table 3.1	The development of genetic concepts for iron-formations before the 80s.	31
Table 3.2	Partial chemical composition of some iron facies.	34

Table 5.1	Commodity analysis.	49
Table 5.2	Comparative Ranking of Some Major Iron ore Regions.	54
Table 5.3	Forecast for steel output.	57
Table 5.5	Ore specifications for iron ore product.	60
Table 6.1	Ranking of mineral terms, arranged in order of increasing precision, compared with the terms used in this thesis.	64
Table 6.2	Comparison of various reserve-resources categories used by the USBM/USGS, Australasian IMM/AMIC and the Thabazimbi mine district.	70
Table 6.3	Comparison between the significant features for sampling purposes of a stratiform deposit and Kwaggashoek East.	73
Table 6.4	Grade and tonnage values for different cut-off grades.	91
Table 6.5	Percentage tonnage for each grade quality type defined in relation with iron and phosphorus content.	94
Table 6.6	Grade quality increase by progressive exclusions.	96

APPENDICES

Appendix 6.1	Geological codes used in the Thabazimbi district.
Appendix 6.2	Mineral classification Thabazimbi.
Appendix 6.3	USBM/USGS classification of Resources and Reserves.
Appendix 6.4	IMM/AIMM classification of Resources and Reserves.
Appendix 6.5	Statistic analysis for low grade ore (Fe>55%) in Kwaggashoek East deposit.
Appendix 6.6	Statistic analysis for high grade ore (Fe>60%) in Kwaggashoek East deposit.
Appendix 6.7	'Down the hole' semi variogram for high grade - lowfos, good quality ore.
Appendix 6.8	'Down the hole' geostatistic analyses for low grade - highfos area.
Appendix 7	Geological section of Kwaggashoek East deposit showing phosphorus content plotted down the borehole trace depicting highfos and lowfos areas.

I INTRODUCTION

The aim of this work is to analyse the geological, genetic and some general economic aspects which might influence the ore reserve estimation of an iron ore deposit. The philosophy and methodology was conducted as far as possible in such a way as to be applicable to any kind of deposit, although each occurrence is unique and needs to be treated individually to be understood, evaluated and developed to suit its own needs.

Kwaggashoek East iron ore deposit was chosen as a suitable field of study for the purposes of this thesis. It is a tabular type of mineralized body with regular and predictable features and its database was available. In addition, the author was involved in the modeling of the deposit and has a general knowledge of this type of occurrence.

The research was divided into two sections. The aim of the first section (A) was to provide a good understanding of the mineralized body with regard to the factors that control its development and subsequent modification. The greater our understanding of the mineralized body, the better chance we have of being able to evaluate it properly. In this section, the term "ore" was intentionally avoided, in order to keep the geological occurrence separate from the economic constraints that define the limits of the ore definition. However, the distribution of some deleterious elements was analyzed because the final aim of any mining activity is a proper final product which is economically viable.

A list of positive and negative geological and genetic factors which might influence the mineralized quality and which should therefore be taken into account for ore reserve estimation purposes is included.

The aim of the second section (B) is to analyse the ore reserve estimation process. The interrelationship between geology and economics in the mining environment led to perform a commodity analysis that forms the first part of this section.

Ore reserve terminology is reviewed and discussed in order to clarify the basis of the procedure. The sampling and the estimation methods are analysed with regard to the final estimation. Emphasis is placed on the fact that ore reserve estimation is not a simple calculation and that grade is not synonymous *with* average assay. The impact of phosphorous is given as an example of a deleterious element in order to introduce the concept of a grade-quality/tonnage curve.

SECTION A - GEOLOGY AND GENESIS

II GEOLOGICAL SETTING

2.1 Regional Geology

In southern Africa, iron-formations occur in different types of tectonic environment, namely greenstone belts, metamorphic mobile belts and cratonic basins (Beukes, 1973).

The Thabazimbi iron-formations were deposited in a cratonic environment located in the northern part of the Kaapvaal Craton, south of the Limpopo metamorphic belt.

The Thabazimbi iron-formations are part of the Transvaal Sequence which is preserved in two structural sub-basins. One is developed in the Transvaal Province, in parts of the Orange Free State and in Eastern Botswana and is referred to as the Transvaal or north-eastern sub-basin. The other is located in the Northern Cape Province and adjoining parts of Botswana and is referred to as the Griqualand West or south-western sub-basin (Fig. 2.1).

In the Transvaal area, the sub-basin center is occupied by the Bushveld Igneous Complex. An outstanding feature of the Transvaal and Griqualand West basins is that many of the lithological units may be correlated over long distances (Fig.2.1). The similarity of the rock units in both regions can be ascribed to deposition under stable conditions in a cratonic environment.

The Thabazimbi region is characterized by sedimentary and volcanic rocks of the Transvaal Sequence (Fig.2.2) which overlie gneisses and granites of the Kaapvaal Craton. To the northeast, the Transvaal Sequence is overlain by rocks of the Waterberg System. The available geochronology suggests that Transvaal sedimentation probably commenced approximately 2300 to 2400 Ma ago and was terminated some time before Bushveld rocks were intruded 2100 Ma ago (Button, 1986).

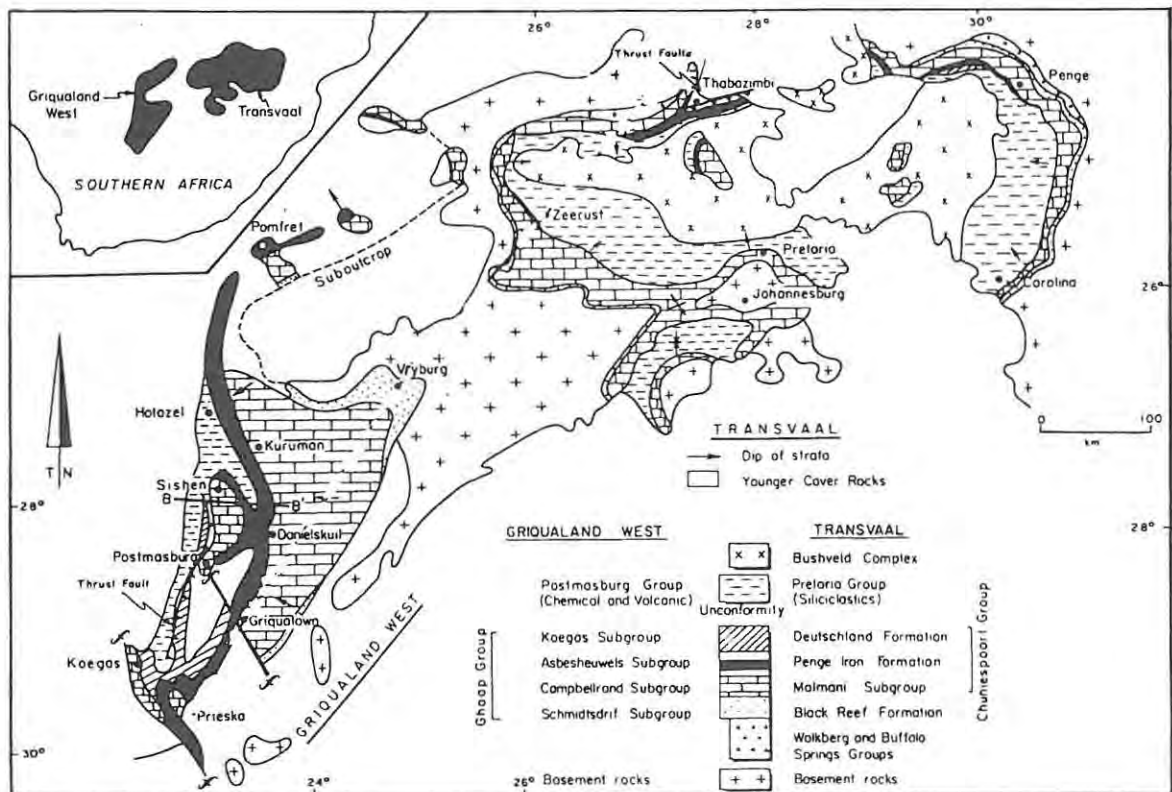


Fig. 2.1 Geologic map showing the distribution of the Transvaal Sequence in the Transvaal and Griqualand West areas and their associated iron-formations. (Modified from SACS, 1980 and Beukes, 1983).

The Transvaal Sequence includes the Chuniespoort Group and the Pretoria Group (Fig.2.2). The iron ore deposits occur at the top of the Chuniespoort Group in the basal portion of the Penge formation. The Chuniespoort Group consists mainly of dolomites (Malmani Subgroup), which overlie the quartzites, shales and conglomerates of the Black Reef Formation (Fig.2.2).

The Penge Formation overlies the dolomites of the Malmani Subgroup and consists of a chert-rich shale, succeeded by about 350m of ferruginous rhythmites (banded iron-formations, BIF). A paleokarst topography was developed prior to the deposition of the basal shale of the Penge formation (Fig.2.2).

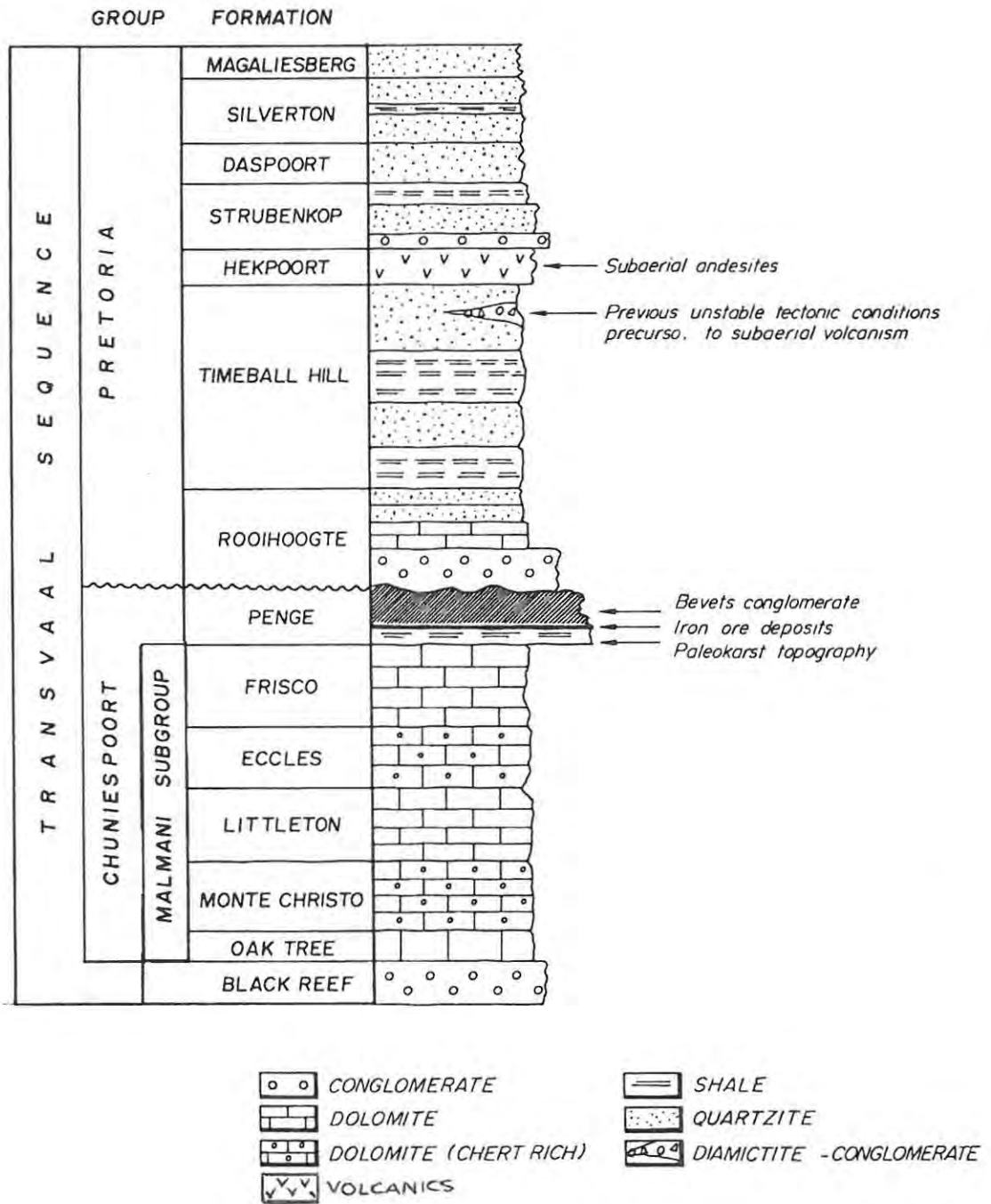


Fig. 2.2 Schematic lithostratigraphic column of the Transvaal Sequence in the Thabazimbi area. (Modified from Boardman, 1948; SACS, 1980; Van Deventer et al., 1986 and Eriksson et al., 1988).

The Penge Formation is in turn unconformably overlain by ferruginous shales of the Timeball Hill formation or directly by the Bevets conglomerate of the Rooihogte Formation (Fig.2.2). The basal Rooihogte Formation, comprising chert breccia/conglomerates, overlying shales and uppermost quartzites, is thought to represent alluvial fan and succeeding fan-delta deposits (Eriksson et al., 1988). During the Rooihogte development, initial graben formation is presumed to have led to the deposition of residual cherty material, derived from karstic weathering of the Malmani dolomites which underlie the Pretoria group, on alluvial fan complexes. This deposition reflects a drastic change in the paleoenvironment of the basin.

Unstable tectonic conditions of the basin are reflected in the diamictites of the upper portion of the Timeball Hill formation being precursors to the subaerial volcanism of the Hekpoort Formation. Basaltic andesites of the Hekpoort Formation in the basal portion of the Pretoria Group have been dated as $2224M \pm 21$ years old (Button, 1986). The Hekpoort andesites (Fig.2.2) are overlain by conglomerates of the Strubenkop Formation, further reflecting the unstable conditions.

Lacustrine conditions became established with the shales of the upper portion of the Strubenkop Formation and once again with the shales of the Silverton Formation, attributed to a deepening of the depository and anoxic sedimentation. The mature Magaliesberg quartzites reflect the termination of the depositional history of the basin in the area, representing extensive shoreline reworking of delta deposits.

Around the Bushveld Complex, the Transvaal strata dip homoclinally towards the Complex at angles of between less than 5° to over 40° . In general, dip angles increase towards the Complex (Button, 1986), which suggests that tilting of the strata was due to accommodation of the large volumes of basic magma (Button, 1986).

The Transvaal Sequence in the Thabazimbi area is intruded by the Bushveld Complex, which led to contact metamorphism in the dolomites and iron-

formations. No specific studies of metamorphism have been undertaken in this area. A comprehensive study of the Transvaal Sequence in relation to metamorphism (Button, 1976), shows that the sediments and volcanics were metamorphosed both by intrusive sills and by the Bushveld Complex. The metamorphic effects of the Bushveld Complex cut across stratigraphy and extend down to the Malmani Subgroup dolomite in places where tremolite, scapolite, biotite and some garnets are developed (Button, 1973). Grunerite rosettes are frequently found in the Penge iron-formation. The Pretoria Group shales were converted to coarsely crystalline hornfelses containing andalusite, cordierite, staurolite, biotite and some garnets. At the highest metamorphic grades, quartzites are recrystallized to very coarse mosaics, and shales undergo partial melting and plasticization (Button, 1986).

A close association exists between large reverse faults and iron ore deposits in the banded iron-formations (BIF), in the Northern Cape Province and in the Transvaal area. A geological and Bouguer anomaly contour map of the Transvaal Sequence and Bushveld Complex within the Transvaal basin indicates an alignment of the anomalies, trending nearly EW, in relation to the mentioned reverse structures in the Thabazimbi area. The faults, as well as the Bouguer anomaly and the iron-formation outcrops are interrupted to the east, north of the Warmbad area (Fig. 2.3), where a paleohigh has been interpreted (Eriksson et al., 1988).

The structural pattern in the Thabazimbi area led to the duplication of the banded iron-formation (BIF) due to east-west striking reverse faults (Fig. 2.4). The complexity of the structures south of the Thabazimbi area cannot be illustrated satisfactorily in a two dimensional view, due to the development of flower structures in different directions along a fault system (Du Plessis and Clendenin, 1988). The final tectonic event in the Thabazimbi area, is represented by a northwest-southeast set of tensional Post-Karoo faults, many of which are intruded by dolerite dykes.

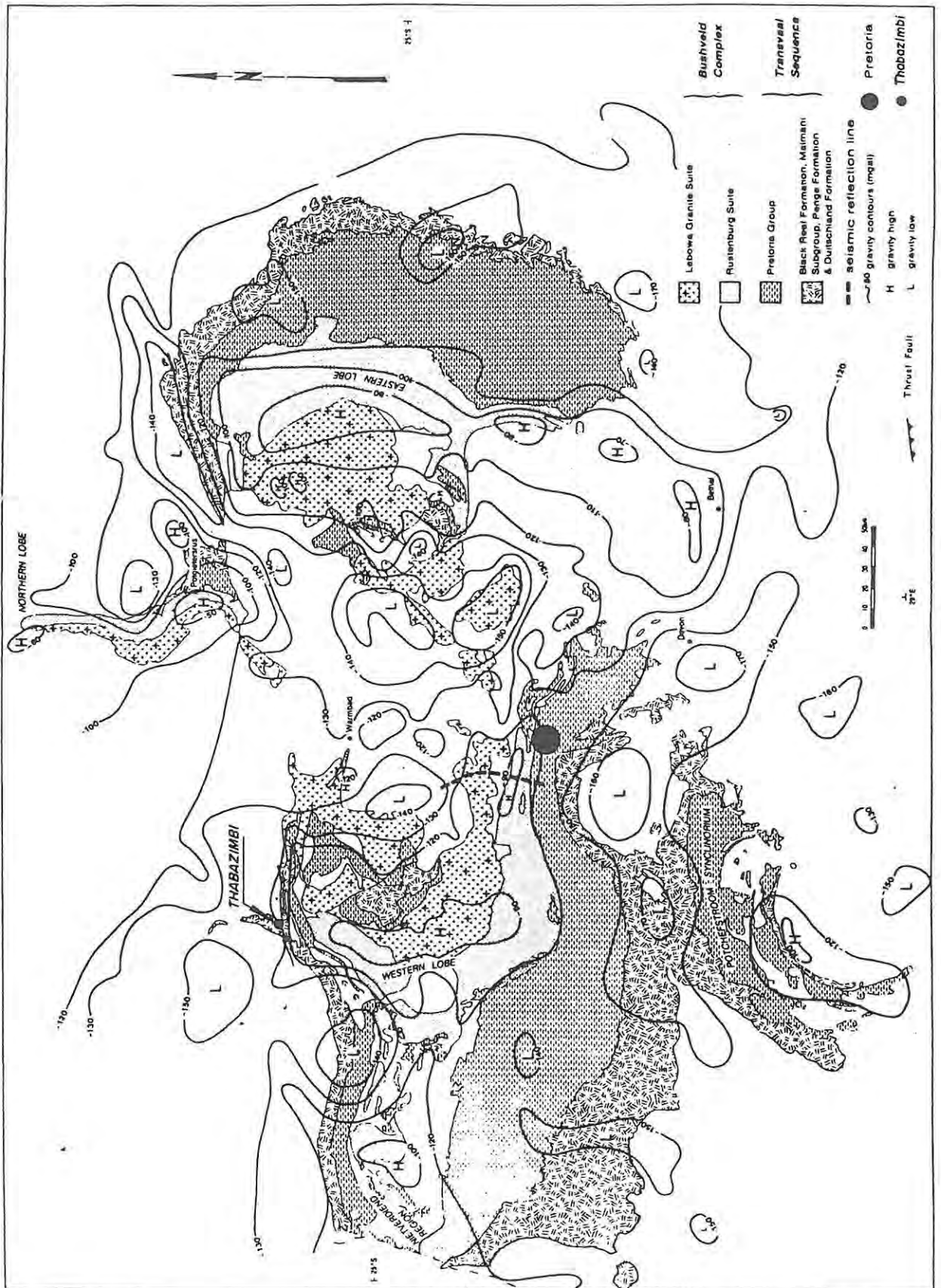


Fig.2.3. Geological and Bouguer anomaly contour map of the Transvaal and Bushveld Complex within the Transvaal Basin (Modified from Eriksson, et al., 1988)

2.2 Local Geology

The Kwaggashoek East iron ore deposit is located in the Thabazimbi area, north-western Transvaal about 180km north-north-west of Pretoria. This deposit forms part of a chain of iron occurrences (Fig.2.4) with similar lithology, mineralogy and geochemistry (Van Deventer et al., 1986).

In this area, rocks of the Transvaal Sequence generally strike roughly east-west, dipping about 30° to 65° to the south. The area is structurally complex and is characterized by a number of east-west-striking faults which have led^{to} the duplication and, in parts, the triplication of the banded iron-formations (Fig 2.4). A very complicated structural pattern was described south of Thabazimbi with a vertical mylonite zone flanked by steep reverse-fault planes, forming a flower structure (Du Plessis and Clendenin, 1988). Previous interpretations, however, have accounted for the duplication of strata by a mechanism of thrust faulting (Strauss, 1964; Fourie, 1984).

Subsequent differential erosion has produced prominent parallel mountain ranges with very steep northern slopes of dolomite, and steep southern dip-slopes of banded iron-formations.

The Kwaggashoek East deposit is located in the northern Range, where the mining activities^{are} at present being conducted. It represents the most eastern deposit of the chain (Fig 2.4).

The ore body occurs in the basal portion of the Penge Formation. It wedges out laterally to the east and is bounded by a dolerite dyke to the south-west. These intrusive bodies are associated with a north-west faulting pattern attributed to Post-Karoo tensional deformation. They occur as marginal or bounding dykes to other deposits along the chain (Fig.2.4)(Van Deventer et al., 1986).

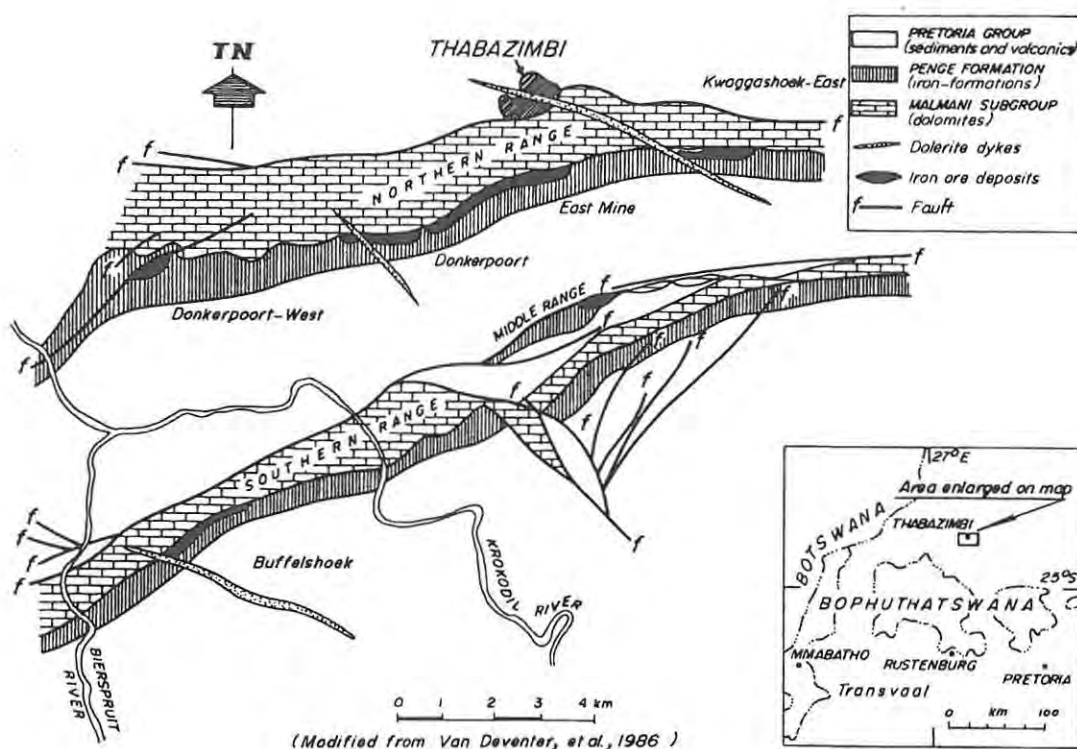


Fig.2.4 Geological sketch map of the Thabazimbi mining area (Modified from Van Deventer et al., 1986).

2.2.1 Lithology

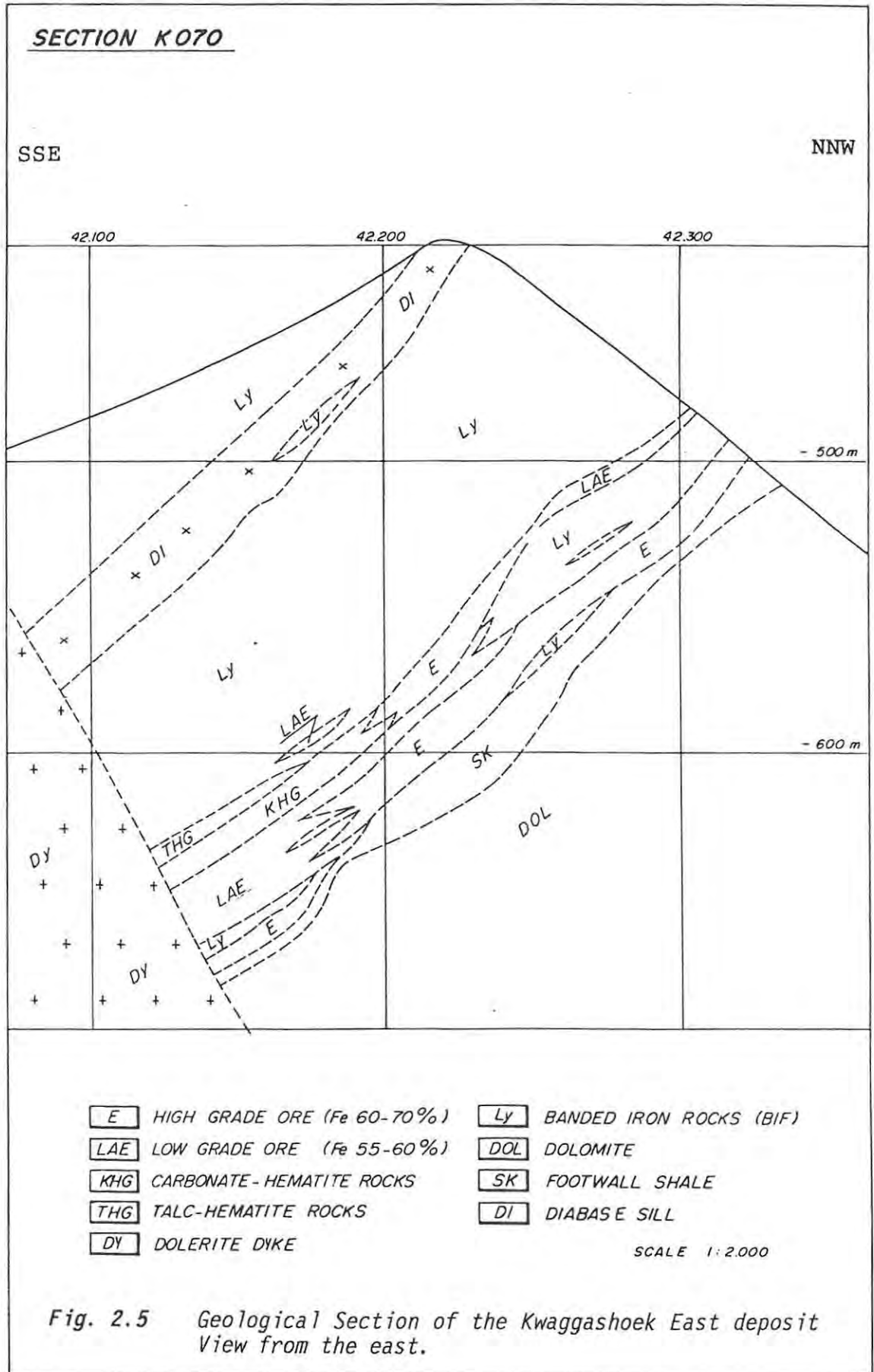
A typical section of Kwaggashoek East is shown in Figure 2.5. Footwall shales and dolomites are overlain by the main iron zone which occurs near the base of the banded iron-formations. The deposit is bounded by a dolerite dyke and a diabase sill intrudes the BIF lithologies.

The footwall dolomite forms part of the upper portion of the Frisco Formation. It consists of three distinct types of material: i) a massive to laminated grey dolomite, usually interbedded with thin layers of graphitic shale, ii) a crystalline and usually highly jointed pink dolomite, with irregular patches of wad, iii) a discoidal dolomite consisting of dolomite disks in a shale matrix. Type (iii) has been identified mainly at East Mine and Donkerpoort (Fig.2.4) but not at the present stage of this research, at Kwaggashoek East.

The importance of the footwall dolomite and its relationship with the mineralization process have been pointed out by previous researchers (Van Deventer, 1985 Van Deventer et al., 1986). Solution of the uppermost dolomites took place forming depressions that led to the collapse of the Penge Formation with concomitant brecciation of the iron-formations. Sinkholes have also been described in the dolomites; these are filled with brecciated iron-formation in a shaly matrix, or by brecciated talc-hematite and carbonate-hematite rocks (Van Deventer et al., op. cit.). According to Van Deventer et al. the ferruginization within the ore bodies displays a direct correlation with the brecciation of the Penge Formation. Near the top of the Frisco Formation (dolomites), a marker band of chert has been regionally recognized, immediately overlain by a zone of discoidal dolomite. This marker serves as a reliable guide in determining the degree of dissolution that the uppermost dolomites have suffered. Its position fluctuates between 1m and 100m below the Penge Formation.

The footwall shale is the basal strata of the Penge Formation. It forms an irregular unit with a variable thickness of between 2m and 20m. In places it wedges out, leaving the dolomite as a footwall in contact with the iron ore. The shale is interbedded with finely laminated chert being cherty rich in the southern side of the dolerite dyke which bounds the mineralized body (sections K0 56-60). Its colour is black to dark grey and it exhibits variable weathering. Brecciation of this unit is normal due to solution of the underlying dolomite. The contact with the underlying dolomites is gradational, with lenses of dolomite in the shale and also "shale-rich" dolomite above the footwall shale proper. The contact with the ore body is normally sharp. However, the shale displays slight ferruginization in some areas.

Despite the fact that the brecciation of the footwall shale and the ore body has been attributed to the same process of solution of the underlying dolomites, some cores display the brecciated ore overlying a very well laminated shale unit (Plate 3.1, chapter III). This fact



suggests the existence of other contemporaneous factors that could cause the brecciation of the ore body and the concomitant ferruginization process.

The sharp contact between the footwall shale and the mineralized body is an important feature in the development of any subsequent mining process. This sharp contact has led to minimization of any footwall dilution, especially regarding deleterious elements such as aluminum and potassium. From a rock slope stability point of view, the sharp contact between the shale and the orebody has been determined as an important factor in a failure which occurred in the Vanderbijl Pit, located in the Northern Range, where the Kwaggashoek East deposit is located (Graham, 1989). Before the failure, big cracks developed in the surface along the the footwall shale contact, due to underground mining activities.

The banded iron-formations are thinly bedded, composed of alternating laminae; a few millimetre to over 2cm thick, of grey to pink chert and iron oxides. The latter laminae are composed mainly of martite enclosing remnants of magnetite, with varying proportions of secondary hematite and limonite, and some chert (Strauss, 1964).

A complete type section through the Penge iron-formation at Thabazimbi is shown by Van Deventer et al. (1986, p. 926). It includes the normal nomenclature used for banded iron-formations in South Africa (Beukes, 1980). This nomenclature was intentionally avoided in this thesis, because it is considered mainly applicable for the purposes of fine stratigraphic studies.

The banded iron-formations show contortions and also local brecciation. In places the brecciation is obviously due to slumping, as a result of solution of the underlying dolomite, but in places the brecciation seems to have taken place prior to or during the formation of the iron ore deposits. The banded iron-formation contains an average of about 35% Fe in the district, increasing to 39.6% Fe in the Kwaggashoek East deposit (See iron in Geochemistry, Fig. 2.7) and varies from being non-magnetic to strongly magnetic.

The mineralized body is found at the base of the banded iron rocks of the Penge Formation, above its lowest shale unit. It is an irregular tabular body 700m along strike, with an average thickness of 30m. Its attitude is parallel to the bedding (N80E/ 45SE). The body wedges out laterally to the east and is bounded by a diabase dyke to the west (Fig. 2.5). In depth, the mineralized body passes laterally into carbonate-hematite and talc-hematite rocks (Fig. 2.5).

The texture of the mineralized body is normally brecciated, primary hematite fragments set within a secondary hematite matrix (Plate 2.1). Laminated and massive textures of the ore are also found in the deposit, mainly between the levels -550m and -620m (Fig. 2.5).

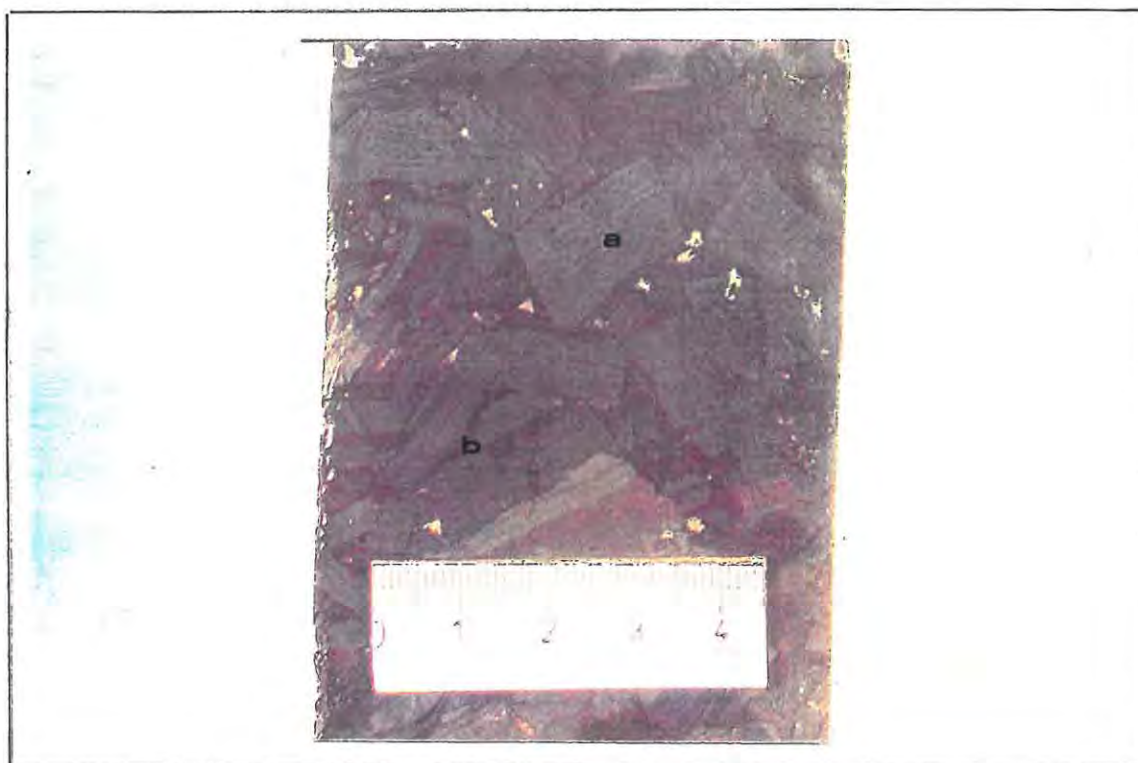


Plate 2.1 Typical brecciated ore: primary hematite fragments (a), set within a secondary hematite matrix (b)

The proportions of primary and secondary hematite in the mineralized body vary and are influenced by the amount of chert in the rock and the thickness of the original banding. The colour of the primary iron oxides varies from steel-grey to blue-grey with a metallic lustre and a dense compact texture. The secondary hematite is red brown (Plate 2.1).

The diversity of texture and forms makes it difficult to identify objectively primary hematite in highly ferruginized rocks. Hematite in banded iron-formations cannot be said to have a typical morphology or texture, since it varies widely in form from minute platy inclusions within chert grains to massive anhedral aggregates. Individual morphological types tend to dominate in a single mesoband, with adjacent bands sometimes containing different forms.

The Thabazimbi mineralized body is composed mainly of quartz (chert) and various iron oxides. It has been proposed that a process of replacement of chert by goethite (FeO(OH)), with martite-hematite rock as an end product took place (Van Deventer et al., 1986). The replacement of the goethite by secondary hematite is well advanced, giving a spongy texture to coarse anhedral crystals. Compared to a provisional maturity scale established for Australian iron ores (Morris, 1980), the Kwaggashoek East mineralized body should be considered a medium mature "ore" based on the degree of supergene enrichment.

Talc-hematite and Carbonate-hematite Rocks

The mineralized body changes in depth to talc-hematite and carbonate-hematite rocks (Fig. 2.5). These rocks are bounded by the dolerite dyke to the west and they wedge out into the mineralized body to the east. Talc-hematite rocks are located in the periphery, forming an aureole around the carbonate-hematite rocks. The stratified talc-hematite and carbonate-hematite rocks occur with mesobands of talc or carbonate alternating with hematite mesobands (0.5-1cm) (Plate 2.2). Brecciation is also common in these rocks, with hematite fragments and mesobands

being enclosed within a talc-rich or carbonate-rich ferruginous matrix. The talc-hematite and carbonate-hematite rocks are closely related to structures such as sinkholes, where karstic collapse of the underlying dolomites has taken place, but are also associated with faults or shear zones near to the dolerite dyke.



Plate 2.2 Carbonate-hematite rock from the Kwaggashoek East deposit

2.3 Geochemistry

The bulk chemical composition of BIFs differ sharply from the composition of common igneous, sedimentary or metamorphic rocks. The main feature of the BIF is the substantial concentration of just one element, iron, in the face of markedly low contents of Al_2O_3 , CaO , TiO_2 , Na_2O and K_2O . (Mel'nik, 1982)

Examination of the geochemistry of the deposit will be focussed mainly on the deleterious elements specified for the final product, which determine the quality of the ore.

2.3.1 Distribution of iron and the main deleterious elements within the mineralized body

The routine analyses performed on the Thabazimbi iron ore are X-ray fluorescence spectrometry (XRF-analyses) of one metre samples for Fe, SiO₂, Al₂O₃, Mn, Mg, Ca, K₂O, P, TiO₂ and S.

In general, the most important deleterious constituents of iron ores are phosphorus, potassium, aluminum, silica, titanium, sulphur, zinc, manganese and arsenic. The ore specifications for the Thabazimbi final product are displayed in Table 2.1. No deviation has been included for the specification values, due to the difficulty of working with ranges of limits instead of simple values.

Table 2.1 Thabazimbi ore specifications for final product (without margins of variability)

	Lump ore	Fine ore
Fe	63.0 %	63.0 %
SiO ₂	6.0 %	4.5 %
Al ₂ O ₃	1.0 %	1.3 %
P	0.05%	0.05%
MnO	0.4 %	0.5 %
K ₂ O	0.09%	0.09%

The Kwaggashoek exploration phase database consists of 78 boreholes with analyses of the mentioned elements giving a total of 1830 samples within the project area.

Histograms displaying the range of concentrations of the deleterious elements were constructed in order to analyse their general population distributions (Fig. 2.8; 2.9). Those elements with a mean close to the specifications for the final product, were spatially analysed. In appendix 7 an example is shown of the levels of concentrations of phosphorous, plotted alongside the borehole trace in a geological section. The same procedure was carried out for iron, silica, manganese and aluminium.

Dilution cannot be avoided completely, and the limits of the ore body in terms of planning cut-off grade (See Chapter 6) are susceptible to change depending on economic conditions amongst others. For these reasons, the deleterious elements have been analysed in the context of a universal population that could include subsequent modifications in the cut-off grade. This universal population is attributed to the mineralized body with an iron content over 45% (Fig.2.6). Two subsets of populations were distinguished within this universe, they are: preliminary low grade ore (Fe>50%) and a high grade ore (Fe>60%) population (Fig.2.6).

The average for the main deleterious elements at Kwaggashoek East was computed for the three mentioned populations (Table 2.2), and compared with the lowest value for the final product specifications.

Table 2.2 Average values of iron and some deleterious elements at Kwaggashoek East deposit in three kind of populations

Population	Fe>45%	Fe>50%	Fe>60%	Lowest limit specification for the final product
Name	Mineralized body	P low grade ore	High grade ore	
n samples	1450	764	486	
Fe	59.44	61.3	64.4	63
SiO ₂	6.10	5.4	2.8	4.5
Al ₂ O ₃	1.12	1.05	0.78	1.0
P	0.053	0.055	0.041	0.05
MnO	0.42	0.40	0.389	0.4
K ₂ O	0.042	0.054	0.049	0.09

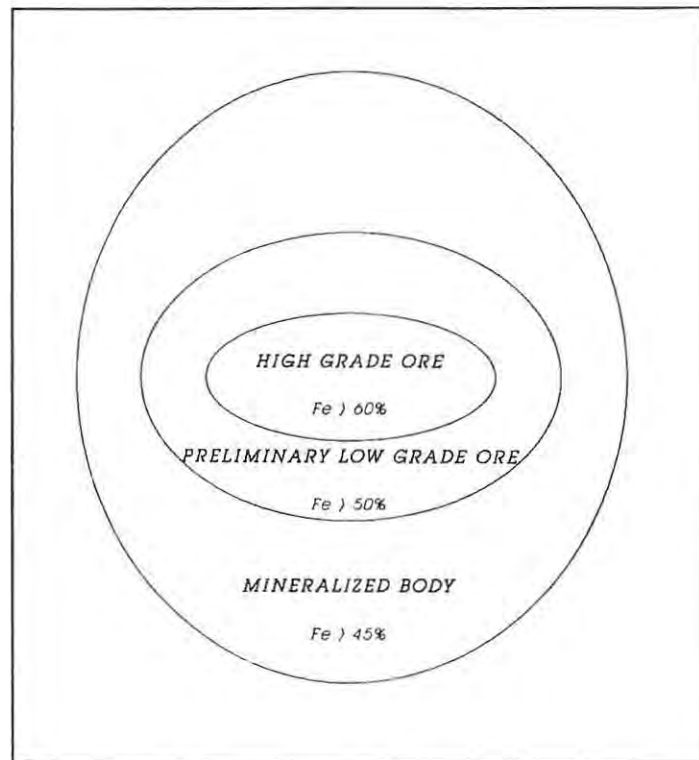


Fig 2.6 Different populations in relation to iron content in Kwaggashoek East iron ore

From Table 2.2, it can be seen that all the deleterious elements decrease in concentration, with an increase in iron content. Almost all of them meet the limit specifications for the final product (not taking into consideration margins of variability) in the mineralized body.

This is an important reason why dilution should be avoided at the time of choosing a mining method.

Iron

Lateral variation within the ore-bearing zone is limited. Where variations do occur, these are due to the presence of lenses of unaltered iron-formation within the ore and to the existence of carbonate-hematite and talc-hematite rocks in depth.

The iron distribution within the mineralized body changes laterally along

strike. High grade (Fe 60%-70%) rocks crop out continuously only in a restricted zone of 300m northeast from the dolerite dyke. The iron content decreases to the northeast. The mineralized body wedges out laterally to finish in a very thin low grade body (2m thick) more or less 600m from the dolerite dyke (Fig. 2.4).

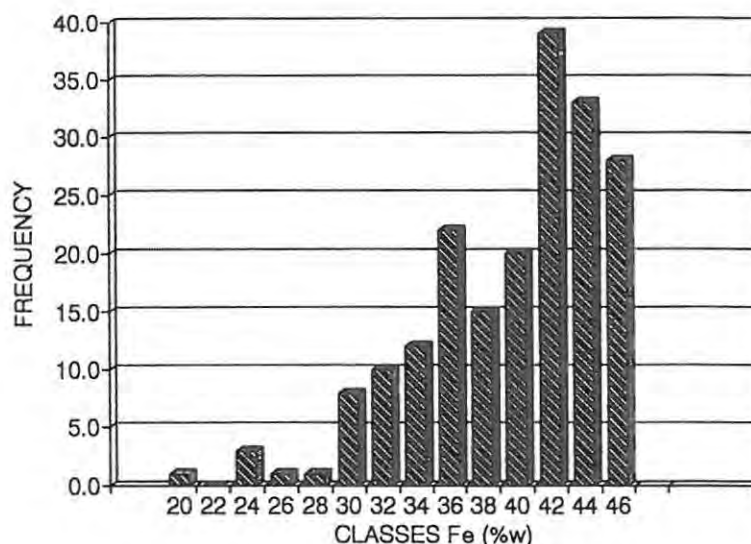


Fig. 2.7 Fe distribution in BIF, Kwaggashoek East iron deposit

The iron distribution within the mineralized body also displays variations with depth. The main factor which contributes to the irregularity of the iron distribution is the presence of talc-hematite and carbonate-hematite rocks which finger out from the dolerite dyke contact (Fig. 2.5). The average iron content in the carbonate-hematite rocks is 40.9% and in the talc-hematite it is 42.8% (Kwaggashoek East drillhole samples).

Vertical variations within the wall-rock iron-formations are also restricted. The mineralized body grades vertically into iron-formation with a decrease in iron values and an increase in SiO_2 . The average content of iron in the BIF is 39.6% (Fig. 2.7), with a concentration in values over 40%, close to or within the mineralized body. The average

iron content in the mineralized body is 59.44% (Table 2.2, Fig.2.8) increasing to 64.4% in the high grade ore (Fig.2.9).

The footwall shale exhibits only local and minor ferruginization concentrated mainly close to the contact with the mineralized body. Iron values in the diabase dyke fluctuate between 13% and 25%, the lowest iron content of the rock suit at Kwaggashoek East.

Silica

The silica content varies inversely with ferruginization of the mineralized body. A negative correlation factor (-0.7) in a Fe-SiO₂ scattergram in a population with an iron content of over 55% might reflect the process of ferruginization that took place through the replacement of chert by iron-oxide minerals. On the other hand, there is no correlation between silica and iron in the BIF rocks of the deposit due to the absence of this secondary process in them.

The average silica content of the mineralized body is 6.1% (Table 2.2), slightly higher than the lumpy ore specification. About 36% of the SiO₂ population is above 6% and 52% is above 4 % (Fig 2.8). The final specification limits for lumpy and fine ore respectively. These parameters suggest that dilution should be avoided as much as possible in order to meet the final product specifications for silica. A contour grid of silica may be useful in determining the grade quality, based on the Fe-SiO₂ negative correlation in the supergene zone.

Aluminum

The Al₂O₃ content in the mineralized body (Fe>45 %) exceeds the ore specifications limit which is 1.0%. (Tables 2.1 and 2.2). Nearly 1500 samples were plotted and compared with the geology, showing that the highest values are associated with talc-hematite rocks in which the aluminum content varies between 3 and 6%. A second category of medium/high values is associated with low grade ore (Fe between 50-60%)

and the footwall shale. Samples of dolomite have about 5% Al_2O_3 on average and the shale displays values between 4.8 and 7% Al_2O_3 . The Al_2O_3 content of the latter is lower than that reported for normal shales which varies between 14 and 15 % (Wedepohl, 1978).

In order to avoid Al_2O_3 contamination, low grade and talc hematite zones of the ore body should be mined with caution. The footwall shale contamination is easier to handle because it is in sharp geological contact with the ore.

The original Al_2O_3 content in two varieties of BIF and a protofacies (Red Sea) (Table 3.2, Chapter III) shows values of above 1% Al_2O_3 which is the specification limit. This would suggest that the secondary processes of enrichment might be responsible for removing this element and decreasing the content of Al_2O_3 in the ore body.

Phosphorus

Phosphorus is a very significant deleterious element for Kwaggashoek East ore. The average phosphorus content in the mineralized body and the preliminary low grade ore exceeds the specification values for the final product ($P < 0.05\%$) (Table 2.2). The frequency distribution of phosphorus in the deposit is similar to other varieties of rock, with a very asymmetric distribution with strongly positive skewness (Fig.2.8; 2.9).

About 35% of the population in the mineralized body ($Fe > 45\%$) exceeds the specification limit ($P < 0.05\%$). In order to determine the spatial distribution of this element, a set of sections were plotted with the phosphorus content in bar graph form down the borehole trace (e.g. Appendix 7). From this work, it was concluded that the highest P concentrations were related to depth, proximity of the dyke and structures interpreted as possible sinkholes. The P content was higher in talc- and carbonate-hematite rocks and low grade ore. A scattergram of P vs CaO shows a very positive correlation that might be related to the presence of apatite.

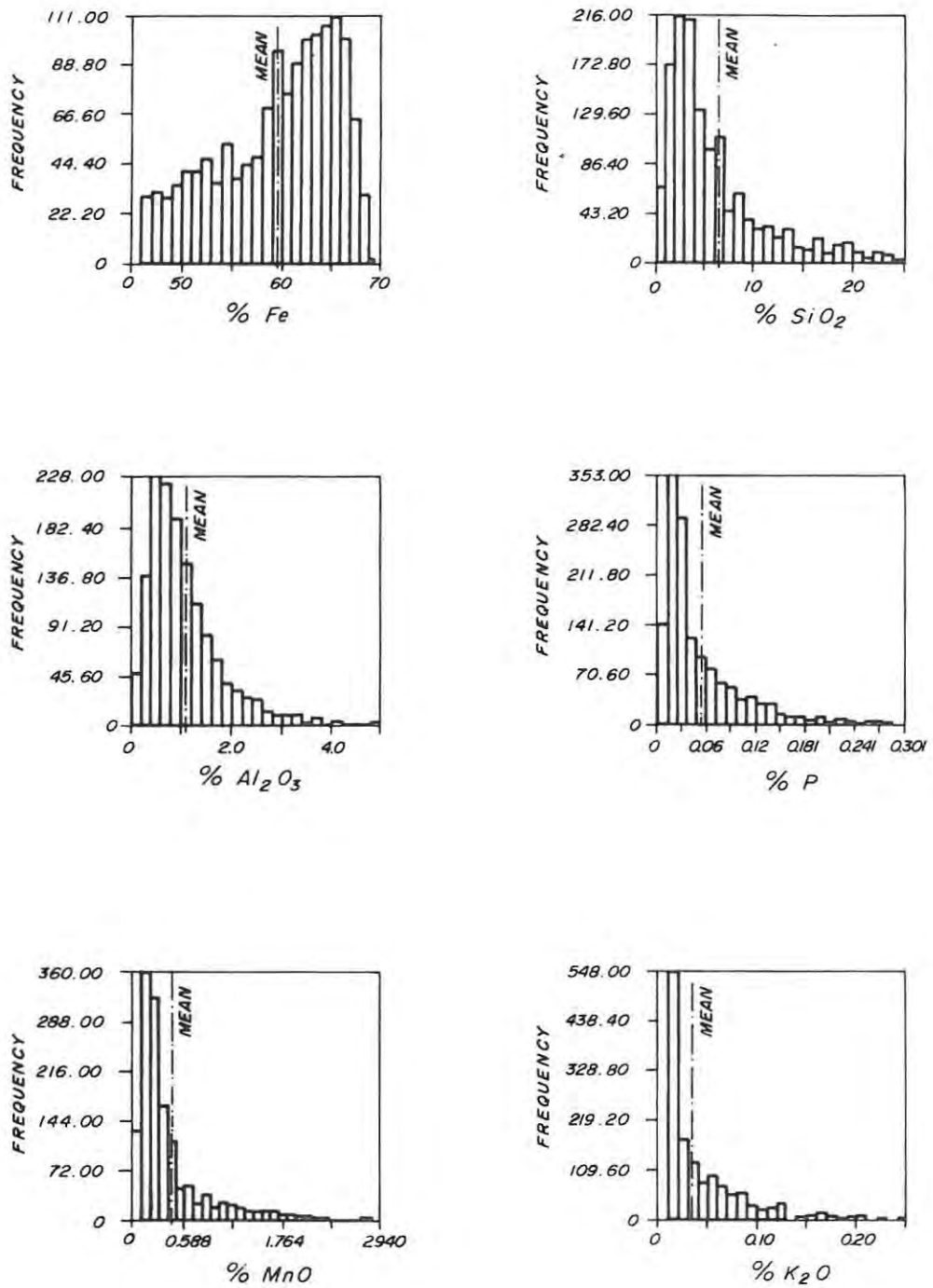


FIG 2.8 DISTRIBUTION OF IRON AND THE MAIN DELETERIOUS ELEMENTS IN THE MINERALIZED BODY (Fe > 45%) KWAGGASHOEK EAST IRON ORE DEPOSIT.

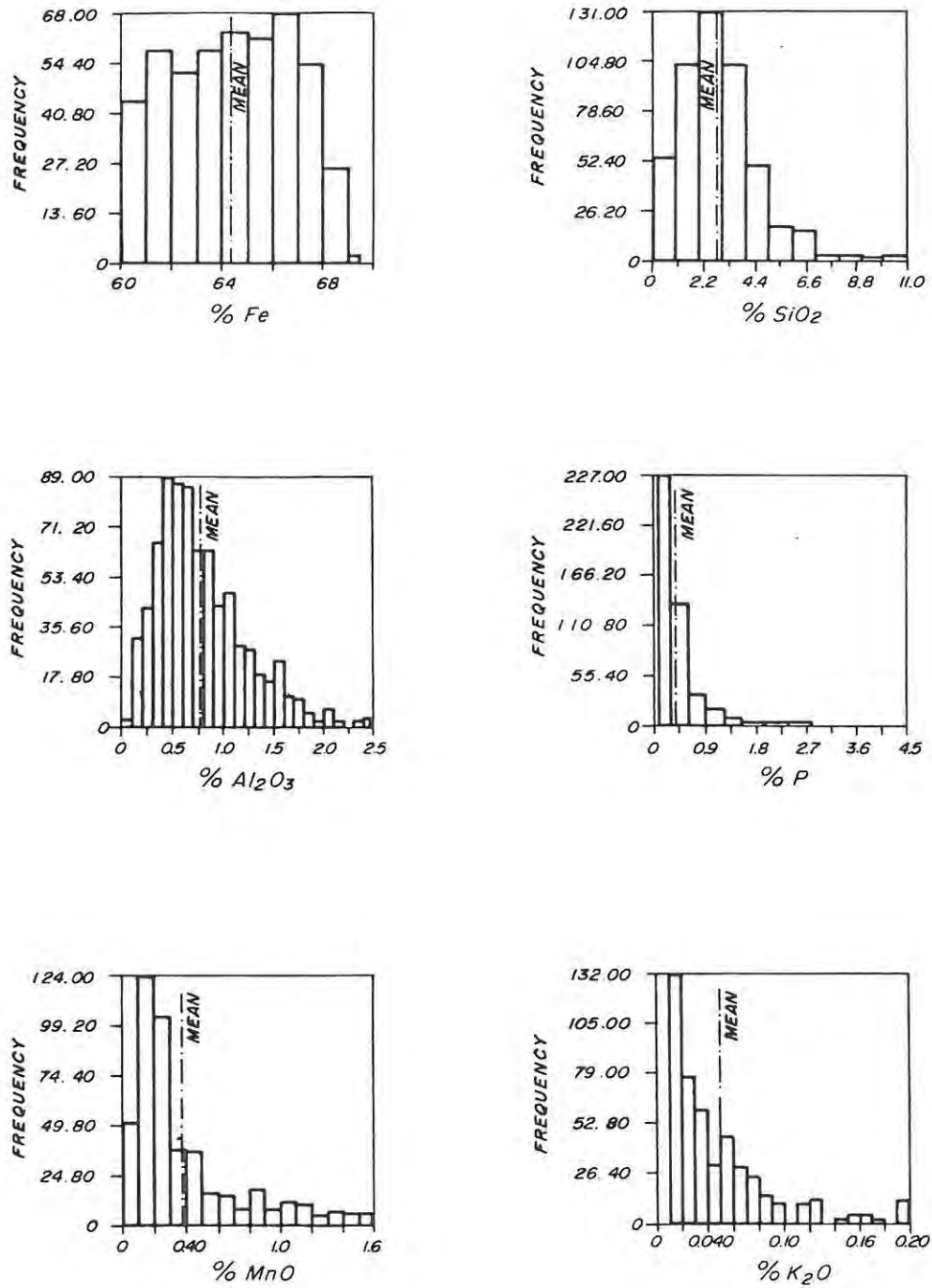


FIG.2.9 DISTRIBUTION OF IRON AND THE MAIN DELETERIOUS ELEMENTS IN HIGH GRADE ORE (Fe 60 %-70 %) KWAGGASHOEK EAST IRON ORE DEPOSIT.

Two main areas were defined according to their phosphorus content. Ore reserves were estimated for **highfos** and **lowfos** qualities for the different types of ore. (See Ore reserve, Chapter VI, subsection 6.9).

The normal BIF at the Kwaggashoek East deposit have a slightly higher (0.07%) phosphorus average than the mineralized body. This reflects a primary source, in comparison with iron-rich volcanogenic sediments from the East Pacific Rise where the phosphate in seawater reacts with poorly crystallized hydrous ferric oxides. These sediments absorb far greater amounts of phosphate from seawater than do either carbonate or non-carbonate sediments from other areas of the ocean (Wedepohl, 1978).

Studies of the erratic phosphorus content of the Hamersley ore in Australia (Ewers and Morris, 1981) suggested that P was evenly distributed across the mineralized area and, thus, that it was the ore forming process that was responsible for the erratic distribution of P in the ores. Phosphorus was mainly present in goethite. This mineral was dissolved by constant ground water movement, leaving pure porous hematite ores. Ores along the Paraburdoo Ridge (Channar deposits, Australia) still contain substantial matrix goethite in places and thus have typically higher phosphorus than the high grade ores (Morris, 1986).

The relationship between high phosphorus content and low grade ore in the Kwaggashoek East deposit could well be attributed to the same process described for the Channar deposits mentioned above.

Manganese

A close chemical relationship between iron and manganese is represented in most of the sedimentary iron-formations. Separation and deposition of both elements is predicted by simple redox reactions in seawater (Schissel and Aro, 1992).

In the Kwaggashoek East deposit, manganese is a deleterious element and is present in concentrations that are very close to the specification

limit for the final product (0.4%, Table 2.5). More than 30% of the population in the mineralized body is above this limit (0.4%) (Fig. 2.8).

For these reasons, the manganese distribution within the ore body was analysed in detail. More than 40 boreholes were plotted in different geological sections (with the MnO content as graph bars) to observe the relationship of MnO with lithology and structures. The manganese content was divided into three classes: a) Low content 0.0 - 0.4% MnO b) Medium content 0.4 - 0.5% MnO; and c) High content 0.5 - 1.6% MnO.

No clear relationship between the manganese content and any specific rock type was found. A slight correlation with the iron distribution, and therefore with the low and high grade ore types was apparent.

The low manganese class was restricted to the ore zone nearest to the surface and to the zone below level -650m, close to the dyke. The high manganese class is spatially distributed between levels -500m and -650m (Fig. 2.5) and associated with possible structures (small faults?) interpreted for that zone in a set of two sections of the central part of the mineralized body (e.g. section K0 78). The presence of high manganese content (wad patches) at the bottom of the mineralized body associated with structures (sinkholes, folds and faults) was observed in other deposits of the Thabazimbi district where the structural pattern is more complicated (Donkerpoort West drillhole database).

The manganese distribution might suggest a primary origin diminished by the supergene processes near surface and by the low metamorphism in depth. The Mn content in BIF is close to that of the Lake Superior type (Table 3.2, in Chapter III). Studies in recent protolithic facies of manganese-iron-formation, indicate that manganese deposition related to recent active hydrothermal fields takes place in areas distal to the hydrothermal vents in the outer margins of the sedimentary basins and manganese is usually transported beyond the main depositional areas for siliceous iron-rich facies (Gross, 1987).

The close chemical relationship between iron and manganese would predict that the same solutions, enriched in iron, may also be an important source of manganese. Separation and deposition of both elements being predicted by simple redox reactions in seawater (Schissel and Aro, 1992).

Potassium

The Thabazimbi ore is inclined to contain lower K_2O values than other iron ore types (e.g. Sishen, Lammers, 1986). The potassium population distribution in the Kwaggashoek East deposit is skewed to the right (Fig. 2.8). In the mineralized body ($Fe > 45\%$), the mean content of K_2O is 0.042 wt% and in preliminary low grade ore ($Fe > 50\%$) the K_2O mean is 0.054%. In the high grade ore the average content of K_2O is 0.049% (Table 2.2). The mean values in all three populations are well below the specified limit (0.09%) for the final product. Only 11% of the high grade ore population is above the limit specification value (Fig. 2.9). For these reasons, potassium is not considered a serious deleterious element in the Kwaggashoek East ore.

Alkalis in general are problematic in blast furnace practice and have a negative influence on coke usage, metal yield and life of refractory materials.

In Sishen iron ore, the K_2O content is directly related to the presence of mica. Sericite is by far the most important K-bearing mineral in all the ore types. In Kwaggashoek East the highest K_2O contents are associated with the footwall shale and a sharp geological foot-wall contact should minimize any foot-wall dilution.

III GENETIC MODEL

3.1 General Concepts

Concepts relating to the origin of iron-formations and associated metalliferous sediments are complex and diverse in nature. Iron-formations are considered to be hydrolithic sediments, their origins being highly controversial (Gross, 1991).

For the purpose of model construction, the generation of an ore deposit involving a hydrous fluid is considered to have four critical aspects:

- 1) A source for the ore constituents,
- 2) Solution of the ore constituents, at least in part, in a hydrous fluid,
- 3) Migration of the fluids after acquiring their metal content,
- 4) Formation of the ore deposit by selective precipitation of certain constituents in response to physical and/or chemical changes as the fluids migrate into new environments.

Therefore models must focus on source, solution of elements, migration and precipitation (Morganti, 1988).

The ore genetic model for the Thabazimbi iron deposits is complicated by the fact that the ore appears to be the final product of more than one genetic process. Source, solution, migration and precipitation of the elements overlap, obscuring a reliable genetic interpretation.

The genesis of the iron ore deposits at Thabazimbi is presumed to reflect deposition of iron during primary chemical sedimentation and subsequent metamorphism and supergene processes (Van Deventer, 1985). In the present study, each process will be analysed separately, by a comparison with similar deposits in relation to geological features, tectonic settings and geochemical characteristics.

The chemical composition of typical iron and manganese oxide facies (Gross, 1990)(Table 3.2) shows nearly 30% iron. Considering that in the Kwaggashoek East deposit, the average content of iron in high grade ore is 64.4% Fe (Table 2.2 in Chapter II), it is clear that about 50% of the mineralized ore body was a product of primary (or diagenetic) processes. Owing to the importance of the primary process it will be analysed in more detail.

3.2 Primary Processes

Although many questions remain to be answered as to the origins of the Precambrian banded iron-formations, it is generally accepted that they are, or have derived from chemical sediments. Iron-formations were defined by James (1954) as a chemical sedimentary rock, typically thinly banded and/or finely laminated, containing at least 15% iron, of sedimentary origin and commonly, but not necessarily, containing layers of chert.

Iron-formations, in a broad sense, are the prototype of a large group of sediments. The stratigraphic sequence exposed in the Thabazimbi area, consisting of dolomite, quartzite, black shale and iron formation (Fig.2.5), is common, with local variations, on all continents (Windley, 1984). Due to their extensive development, the tectonic environments in which they formed are extremely important.

Many manganese and iron ore deposits have been studied separately in the past without recognizing the spatial and genetic relationships of the associated manganese- and iron-rich facies of protore (Gross, 1990). Typical relationships between manganese- and iron-bearing facies are outlined by Gross (1990), giving a better understanding of the metallogeny of these stratified sediments.

The majority of the large Superior-type banded iron-formations (c.f. infra) associated with manganese formed within a single time period from 2500 to 1900Ma. The distribution of these early Proterozoic basins on a

reconstructed sketch map of this period just prior to Proterozoic continental aggregation is presented in Fig.3.1. The iron formations are well distributed throughout the continental nuclei, but the iron-formations with associated manganese deposits are restricted to the proto-Gondwana continents.

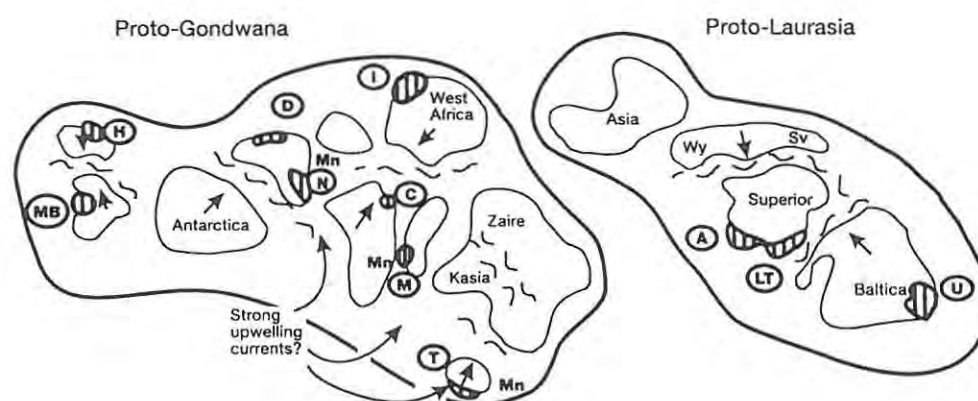


Fig 3.1 Distribution of early Proterozoic basins with major iron-manganese formations on a continental reconstruction prior to Proterozoic supercontinent aggregation. C=Carajas, H= Hamersley T= Transvaal (Modified from Schissel and Aro, 1992).

A broad overview of the development of genetic concepts for iron-formations has been given by Gross (1991). In general, most of the genetic concepts proposed in the first part of this century emphasized sedimentary sources for the constituents. Deposition was thought to have been rigidly controlled in platform or near-shore shelf environments (Table 3.1). Concepts of volcanogenic, exhalative or hydrothermal effusive sources of constituents conceived for these hydrolithic sediments became more common in the second part of this century (Gross, 1991) (Table 3.1).

Table 3.1 The development of genetic concepts for iron formations before the 80s (based on Gross, 1991)

<i>Sedimentary origin</i>	<i>Volcanogenic sources</i>
<i>Weathering processes of iron land areas Leigh, 1903</i>	<i>Volcanogenic origin of Michipicoten iron-formation (Ontario) Collins et al. 1926</i>
<i>Chemical reaction from iron bacteria Chamberlain, 1915</i>	<i>Hydrothermal genetic processes Grout, 1926; Moore, 1931; Bruce, 1933, 1940</i>
<i>Early atmosphere low in oxygen MacGregor, 1927</i>	<i>Oxidation of ferruginous tuffs (Dunn, 1941)</i>
<i>Alteration of seasonal conditions Sakamoto, 1950</i>	<i>Exhalative sedimentary ores (Oferdahl, 1958)</i>
<i>Influence of algae and bacteria Spencer and Percival 1952</i>	<i>Chemical data on thermal springs (Zelenov, 1958)</i>
<i>Varnes in lake water Hough, 1958</i>	<i>Presence of pyroclastics in BIF (Goodwin, 1958)</i>
	<i>Large-scale hot spring and fumarolic activity (Goodwin, 1961)</i>
	<i>Similarities between ancient and recent stromatolites, proposed a hot spring environment Walter, 1972</i>

In the genesis of iron-formations, areas such as primary sedimentary features and facies development, stratigraphic-tectonic environments for deposition, source and transportation of iron and silica, the role of organisms, major iron-manganese-sulfide facies relationships, metallogenic significance, and recent protofacies should be considered (Gross, 1991).

Systematic study of iron-formations, primary sedimentary features, sedimentary and volcanic stratigraphy and tectonic features in a large number of areas led to the recognition of two principal types of iron-formation: Lake Superior- and Algoma-types (Gross, 1980).

Lake Superior-type iron-formations were deposited mainly along continental margins in intracratonic basins, with typical sequences of quartzite, dolomite, black shale, argillite and various volcanic rocks (Fig.3.2). They are associated with extensive rifting, subduction and deep fracture systems that formed during the early Proterozoic, and border or encircle the margins of many Archean cratons and crustal plates (Gross,1991).The depositional basins for Lake Superior-type iron formation were developed and controlled by marginal rifting in these structural belts. Apparently, the continental structures were segments of a major global tectonic system and were developed and active over a long period of time. Extensive hydrothermal effusive activity and volcanism took place along these fracture zones where they crossed areas of high thermal gradients. Therefore it is suggested that the bulk of the constituents in the iron-formations was derived from hydrothermal systems distributed along these fracture zones (Gross, 1991).

On the other hand, Algoma-type iron formations form along fracture systems in volcanic belts. They are associated with greywackes, turbidites, fine-grained clastic sediments and volcanic rocks.

A measure of confusion regarding the classification of banded iron-formations based on depositional environments is pointed out by Ewers (1983). He gives as an example the much-studied unit of Brockman Iron Formation (Australia) which has been classed as a Lake Superior-type (Eichler, 1976; Gross, 1980) and as an Algoma-type (Dimroth, 1976). As classifications are merely an attempt to standardize the parameters of natural phenomena, they should be treated with caution.

The Transvaal Sequence iron-formations have been classified as Lake Superior-type, with the basin interpreted to have developed along the margins of cratons or continental platforms and as having been active over extended periods of time under relatively stable tectonic conditions (Beukes, 1973). Nevertheless, the Lake Superior iron formation at its type locality seems to have developed closer to the craton border than those of the Transvaal Sequence (Fig.3.2), (Gross, 1983).

Table 3.2 shows a partial chemical composition of some oxide iron facies. The Kwaggashoek East set of samples was selected in the mine area, the 212 samples used in this table correspond only to rocks described as banded iron formations (BIF). The Kwaggashoek East sulphur content is slightly higher than the typical Lake Superior type. This might reflect the influence of an original hydrothermal source at the time of deposition, particularly as the higher sulphur contents are concentrated in rocks less affected by the secondary processes responsible for the iron enrichment.

*Table 3.2 Partial chemical composition of some iron facies (wt%)
(Modified from Gross, 1990)*

Type	Lake		Kwaggashoek	
	Algoma	Superior	Red Sea	East
n samples	n=963	n=176	n=43	n=212
SiO ₂	47.8	47.7	9.45	28.2
Al ₂ O ₃	2.6	1.3	1.6	2.5
Ti	0.07	0.02	0.004	0.055
Na ₂ O+K ₂ O	1	0.2	1.8	0.042*
MgO	1.6	1.2	1.1	2.3
CaO	1.7	1.6	4.4	2.93
Fe	30.1	30.9	30.2	31.8
Mn	0.1	0.5	1.3	0.42
S	0.2	0.02	2.8	0.05
P ₂ O ₅	0.2	0.05	0.2	0.07

* Only K₂O analyses available

Source of iron

A comparison with recent protolithic facies of manganese-iron formation shows that the global distribution of protolithic manganese facies on the modern sea floor is related to recently active hydrothermal fields and

takes place in areas distal from hydrothermal vents in the outer margins of the sedimentary basins.

A geochemical and sedimentological study of the facies transition from limestone to iron formation in the Transvaal Sequence (Klein and Beukes, 1989) concluded that the limestone-dolomite-shale lithologies originated in a water column quite distinct from that in which iron-formation was precipitated. The ultimate source of iron (and probably the SiO_2) in the iron formations appears to be a very dilute hydrothermal input in the deep ocean waters, as concluded from mixing calculations of REE values for modern Atlantic Ocean water and hydrothermal solutions from the East Pacific Rise.

The close relationship of the iron, silica and manganese in the carbonate-manganese association of the Transvaal Sequence with a preceding episode of volcanic activity favors a volcanic exhalative hypothesis as a source for these elements (Beukes, 1973).

It appears unlikely that any significant amount of iron would have been transported by river water during deposition of the iron-formations because terrestrial influx was at a minimum during deposition of the iron formations (as shown by the chemical and especially REE composition of the various facies studied by Klein and Beukes (1989) in the Transvaal Sequence. There is also no relationship between the REE patterns of modern river water (Martin et al., 1976) and that of the iron-formations, which would indicate that an evaporite model for the development of the iron-formations, as suggested by Garrels (1987), is unlikely (Klein and Beukes, 1989).

Conduits

In a structural study, 4Km south of Thabazimbi, Du Plessis and Clendenin (1988) describe very complex structures. According to these authors, the complexity of the flower structure is probably a reflection of the degree

of convergence and the configuration of the underlying basement block, for example, a curved fault contact. The complexity may also be due to pre-existing zones of weakness in the basement that have been reactivated during periods of tectonic activity.

The above mentioned flower structure is composed of a central mylonite zone surrounded by lateral faults that seem to have developed at different depths to the central fault. This may suggest reactivation of the main structure with subsequent development of the flower structure.

Strauss (1964) described the main structures as thrust faulting. He also stressed their importance as a decisive factor in the formation of this type of iron deposit although in a sense of 'thermodynamic metamorphism' not totally supported from the present author point of view.

From a comparison of the geology in the Thabazimbi area with the Postmasburg and Boegoeberg areas, and the Lake Superior, Labrador, Quebec, Australia and other iron fields of this type, it appears that an association with large-scale thrust faulting is an essential requirement, among others, for the formation of iron deposits.

The spatial relationship of a major fault with the primary and secondary deposition of the iron seems to be relevant. It is possible that pre-existing zones of weakness might^{have} acted as conduits for the iron and silica to the basin and later they favoured the migration of hydrothermal fluids to contribute to a remobilization of iron, generating a secondary ferruginization enrichment event.

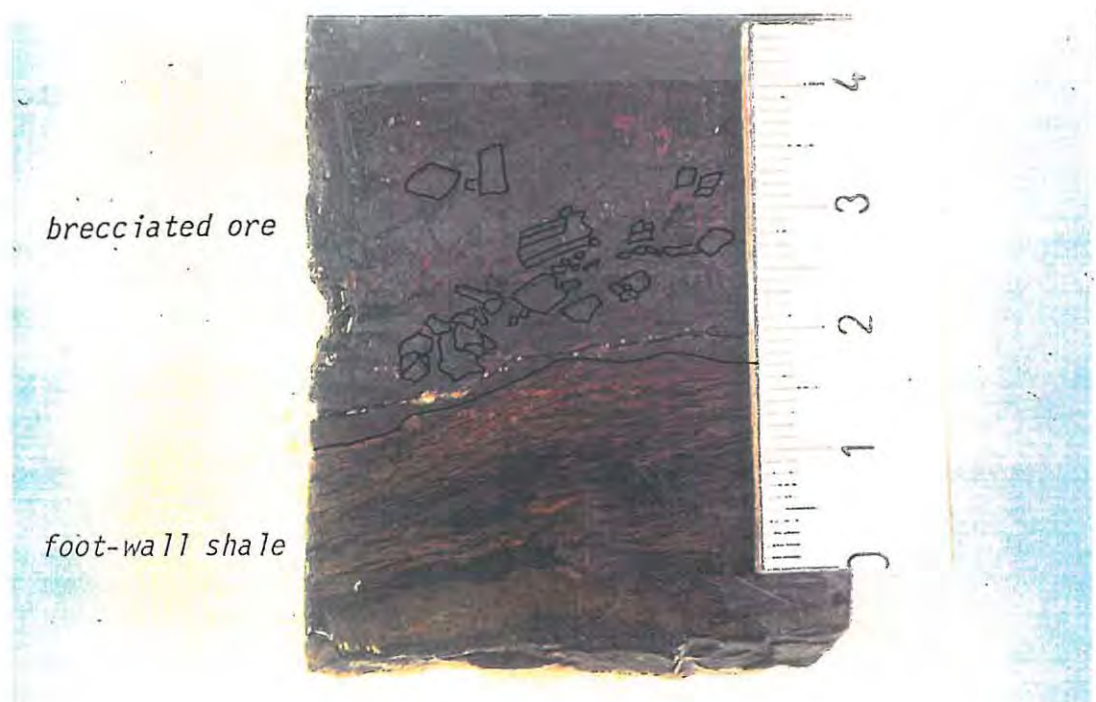


Plate 3.1 *Contact between the foot-wall shale and the brecciated ore body showing the absence of brecciation in the shale.*

As was mentioned in Chapter II, brecciated textures are common within the mineralized body. Brecciation of the banded iron formations is thought to be not only the product of the karst activity that took place in the underlying dolomites. Part of the brecciation might be a product of wave and/or current action or irregularity of the bottom relief. The hypothesis suggested by the author is that part of the brecciation reflects a syngenetic tectonic activity which generated a slight instability in the slope of the basin in local areas during diagenesis of the basal strata. This idea is supported by the fact that in some places, the footwall shale occurs unbrecciated immediately below the brecciated mineralized iron formation rocks (Plate 3.1).

Iron precipitation

The processes for the precipitation of iron by oxidation of Fe^{2+} and hydrolysis of Fe^{3+} to $\text{Fe}(\text{OH})_3$ would have been capable of operating wherever surface waters containing sufficient Fe^{2+} were exposed to sunlight and, for photosynthesis, contained a suitable flora of micro-organisms. It has been argued that the oceans could not have acted as a depleting reservoir from which all of the iron in the banded iron-formations was derived, but that they must have been actively replenished during deposition (Ewers, 1983).

An obvious answer to the problem of the localization of deposition is that the sources of replenishment of iron were close to the area of deposition and yet remote enough to allow the available iron to be distributed sufficiently to the remarkably uniform deposition sites. Mel'nik (1973) reached this conclusion with respect to the supply of both silica and iron from volcanic sources spatially related, but not very close, to the area of deposition.

A composite model for the origin of Lake Superior-type iron formations and for manganese deposits is shown in Figure 3.3 (Schissel and Aro, 1992). This picture provides a simplified view of iron and manganese separation and deposition predicted by simple redox reactions in seawater.

Simple Eh-pH diagrams from Krauskopf (1957) predict that it would be possible to separate iron and manganese in ocean water by gradually raising the Eh under near-surface conditions (Fig.3.3). If deep anoxic, iron-silica-manganese-rich waters upwelled onto a continental shelf, iron carbonate and iron and silica oxides would precipitate first to form a banded iron formation facies.

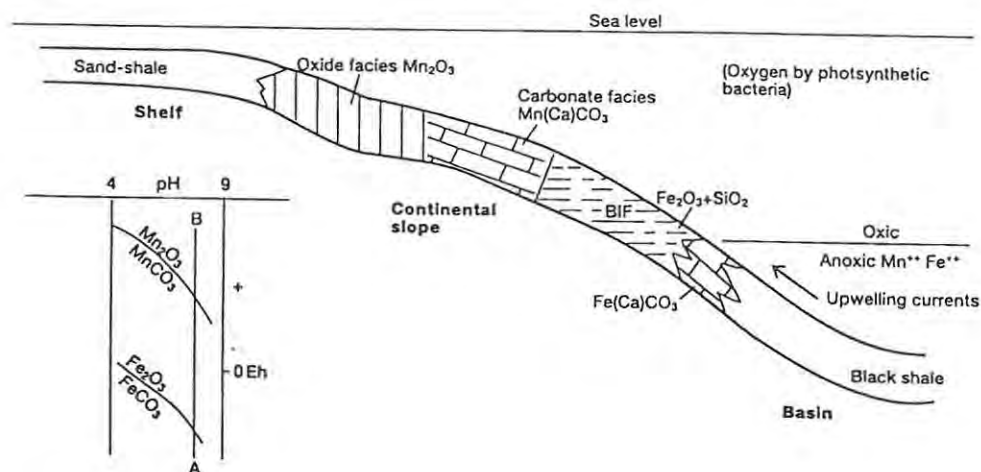


Fig. 3.3 Model for deposition of iron and manganese from upwelling anoxic waters (from Schissel and Aro, 1992)

The absence of economic iron mineralization and the presence of higher manganese contents in the western area of Kwaggashoek East, between this deposit and the East Mine (Fig.2.4), could represent a local topographic high in the basin, that would result in development of facies slightly enriched in manganese (Boreholes KW46 to KW59).

Diagenetic deformation features clearly indicate that both the chert and the iron were deposited originally as colloidal masses. Thus, most of the textural elements are results of compaction, desiccation and diagenetic alteration of the original amorphous precipitate.

3.3 Secondary processes

The Kwaggashoek East database lacks detailed mineralogical descriptions, making it difficult to determine the limit between primary and secondary processes.

A combination of the burial of the banded iron-formations, the intrusion of the Bushveld Complex, the tectonic events which occurred subsequent to the deposition of the iron formation and supergene processes led to the modification of the original rocks.

Late diagenetic reactions are approximately defined by Winkler (1979) as occurring below about 180° C, whereas very low-grade metamorphic reactions would represent a temperature range of approximately 180° C to 300° C.

Metamorphism

Previous studies in the Thabazimbi area suggest the existence of two periods of metamorphism: a contact reaction related to the intrusion of the Bushveld Complex, followed by a second period of metamorphism due to the Waterberg tectonism (Van Deventer et al., 1986). No detailed studies of metamorphism have been undertaken specifically in the Thabazimbi area. Beukes (1973, 1978) made a comparison between the well studied Kuruman Iron-formation of the Griqualand West Basin and the Penge Iron-formation of the Transvaal area. He found that contact metamorphism caused by the Bushveld Igneous Complex has largely obliterated the primary lithological and mineralogical features of the Penge Formation.

The Penge Formation differs from the Kuruman Formation in that it contains no minnesotaite. It has undergone intense amphibolitization, with grunerite replacing many primary minerals. The genesis of the grunerite is complex, but, in comparison with the Kuruman Formation, it can be interpreted mainly to represent metamorphosed minnesotaite. Recrystallization of the quartz, enlargement of magnetite crystals and the replacement of stilpnomelane by biotite are other characteristics attributed to this metamorphic event (Beukes, 1973; 1978). The mineralogical association represents a medium grade of metamorphism according to a table of relative stabilities of minerals in metamorphosed iron formations as a function of metamorphic zone (Pag.460, Klein, 1983).

The changes of the grain size in the chert mesobands is a negative factor for the formation of the mineralized body, making more difficult the dissolution of silica and the subsequent enrichment through a supergene process.

The second period of metamorphism has been mentioned by Strauss (1964), based on observations of the dolomites in zones adjacent to the thrust faults that affected the Thabazimbi area. He suggested that an early metasomatic process of the banded iron-formations resulted from the 'dynamo-thermal metamorphism' and mobilisation of the underlying dolomite during intense thrust faulting. According to Strauss (1964), the first step was the formation of hematite-dolomite and hematite-talc rocks, the former by means of the complete replacement of the chert of the banded iron-formations by dolomite, and the latter by partial replacement of the chert and chemical reactions between the remaining chert and the invading dolomite to form talc. No real evidence and detailed mineralogical studies have been performed to support these ideas. The connection, if there is any, between the formation of the calcareous and talcose rocks and thrust faulting is unclear.

A comparison of relative stabilities of minerals in metamorphosed iron-formations as a function of metamorphic zone shows that talc and calcite can be the product of diagenetic or very low grade metamorphism (Klein, 1983).

If a metamorphic process took place to generate the talc-hematite rocks in depth, it occurred after the tilting of the banded iron rocks to the south. This statement is based on the distribution of this type of rock, restricted to depths below the level -580m (about 200m below the present surface) (Fig.3.4). In Kwaggashoek East these rocks are located in the north-eastern side of the the dolerite dyke that bounds the orebody and have not yet been recognized in the other unmineralized side of the dyke. The presence of talc-hematite and calcite-hematite in the mineralized body decrease the grade quality, because it is also associated with high content of phosphorous.

Supergene enrichment

A supergene replacement model that can account for the properties of the brecciated iron ores found at Thabazimbi is well discussed by Van Deventer (1985). The presence of mineral associations in which one is pseudomorphous after the other, such as magnetite-martite, the absence of wall rock alteration and the existence of lenses of iron formation inside the ore support the occurrence of this process.

The secondary hematite could have been formed by three fundamental steps. Firstly, chert, silicates and carbonates of the primary rock types were replaced by hydrated iron oxides. This was followed by the growth of hematite plates and goethite from the hydrated iron oxides, a process that stopped before all the iron oxides had been altered. Finally, solution of the remaining goethite led to high grade hematite ores. This model, proposed by Morris (1980) for the Hamersley iron ore in Australia is accepted also for the Thabazimbi ore on the basis of mineralogical and textural studies by Van Deventer (1985).

The supergene processes began after the southward tilting of the dolomites and iron-formations. The solution of the dolomites below the Penge Formation led to the collapse and brecciation of the overlying iron formations, talc-hematite and carbonate-hematite rocks. Sinkholes formed locally and became filled with these breccias (Van Deventer, 1985). The deformed basal shales of the Penge Formation acted as a barrier to percolating iron-rich groundwaters.

Another period of supergene ferruginization occurred in post-Karoo times, indicated by post-Karoo fault zones filled with iron ore. Associated post-Karoo dolerites cut one existing orebody and acted as barriers to ground water circulation. An important supergene process might have developed during this time, taking into account that most of the ore bodies in the Thabazimbi district developed to the northeast of these dolerite dykes (Fig.2.4).

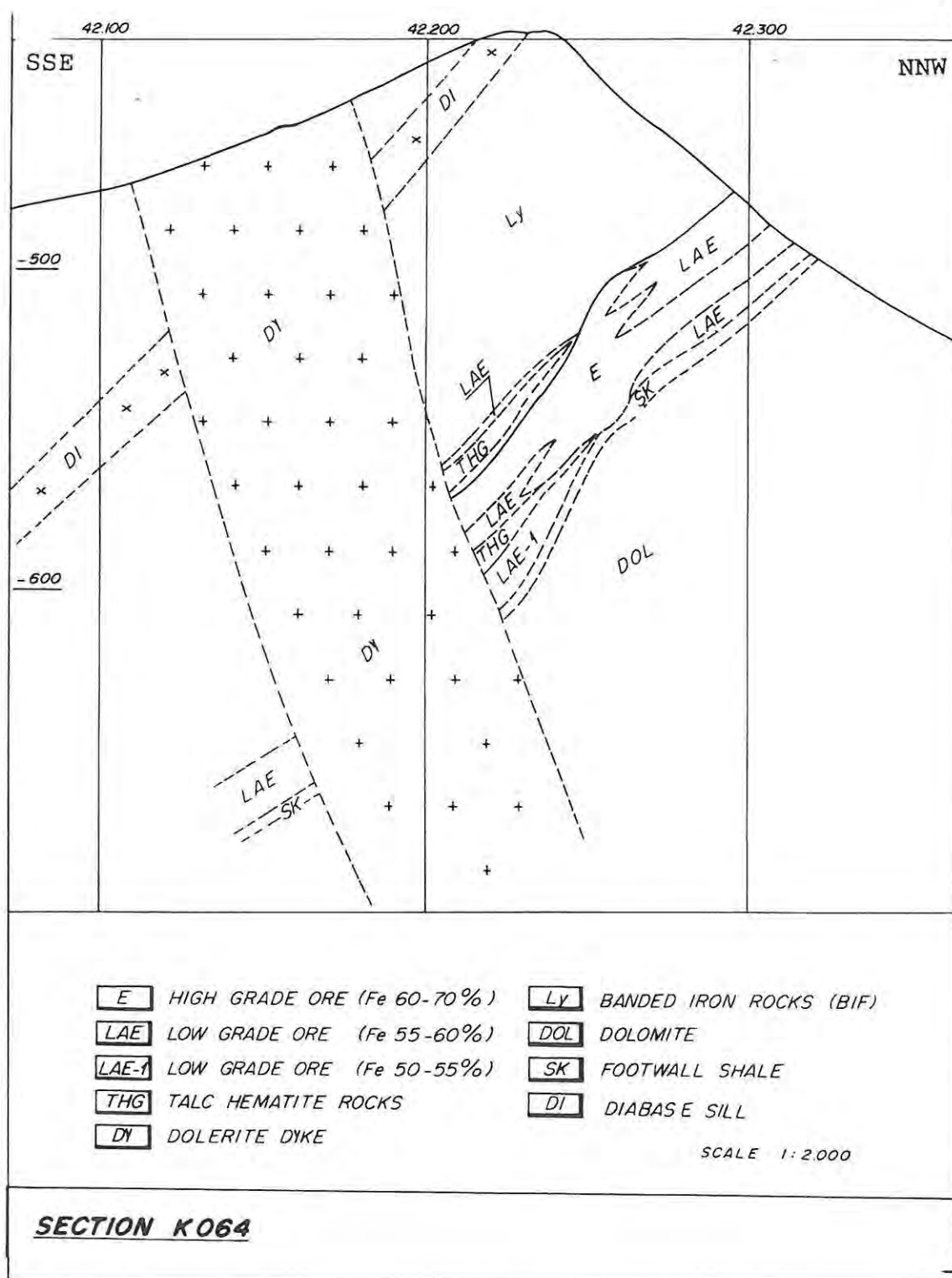


Fig. 3.4 Geological section of Kwaggashoek East deposit showing the dolerite dyke as a barrier for the supergene enrichment and the development of talc-hematite rocks below level -550m in the northern side of the dyke.

The Kwaggashoek East ore body is bordered to the southwest by one of these dolerite dykes. The iron grade changes dramatically from one side of the dyke to the other (e.g. Section K064, Fig. 3.4). This marked change in the enrichment of the mineralized body from the northeast to the southwest suggests two possibilities for the mineralization process: a) the barriers were active prior to the intrusion of the dolerite dyke, or b) the main process of secondary enrichment took place after the intrusion of the dolerite. A simplified model for the genesis of various enriched iron ores from banded iron-formation in the Hamersley Iron Province (Morris, 1986) shows fault planes as natural barriers for the percolating waters.

The post-Karoo faults preferentially developed in areas characterized by sinkholes as these were weak zones; the ore in such areas thus underwent a second period of supergene enrichment (Van Deventer, 1985).

IV CONCLUSIONS

From the general overview of the main characteristics of the Kwaggashoek East mineralized body (Chapters II and III), two kinds of factors may be distinguished: Positive factors, which contribute to the upgrading of the mineralized body, and negative factors which reduce ore grade or particularly quality and thus significantly reduce the potential ore reserves.

Positive factors

- * The close relationship between regional faulting and the distribution of the iron ore deposits.
- * The complicated structural pattern which led to the duplication and often to the triplication of mineralized zones.
- * The paleokarst topography generated by a karst activity that took place just above the groundwater level, which led to the epigenetic ferruginization of the brecciated zones in the mineralized body.
- * The basal shales of the Penge Formation which acted as barriers to percolating iron-rich groundwaters.
- * The associated post-Karoo dolerite dykes which acted as barriers to groundwater circulation and led to a second period of enrichment.
- * The tilting of the strata before the main supergene enrichment period which favoured the percolation of groundwater.
- * The aluminium content restricted mainly to the footwall shale unit that can be rejected selectively from the overlying ore.

- * The low potassium content in comparison with other kinds of ores
- * The negative correlation between silica and iron within the high grade mineralized zones.

Negative factors

- * The contact metamorphism in the banded iron formations due to the Bushveld Complex intrusion which led to the change of the chert grain size in the mesobands, making more difficult the dissolution of silica and the subsequent iron enrichment through supergene process.
- * The development of talc-hematite and calcite-hematite rocks in depth.
- * The phosphorous content associated with sinkholes and folds adjacent to the dyke and with low grade and talc-hematite and carbonate-hematite rocks.
- * The close chemical relationship between iron and manganese and the development of wad pods associated with depressions in the paleokarst topography.
- * The significant alumina content associated with talc-hematite rocks in depth.
- * The complicated structural pattern that although being a positive factor in the duplication of the mineralized bodies, also influences the continuity and regularity of the bodies.
- * The contact with the footwall shale and the overlying orebody which played a major role in previous failure mechanism in neighbouring deposits (Graham,1989).

SECTION B

ECONOMICS AND ORE RESERVES

V ECONOMIC INTRODUCTION

Geology is not an isolated science in the mining environment. Ore reserves are not just a physical and unchanging mass in the ground, they are also subject to a wide spectrum of economic, metallurgical and mining conditions. Figure 5.1 depicts examples of the type of questions that may arise when trying to assess an ore reserve estimation.

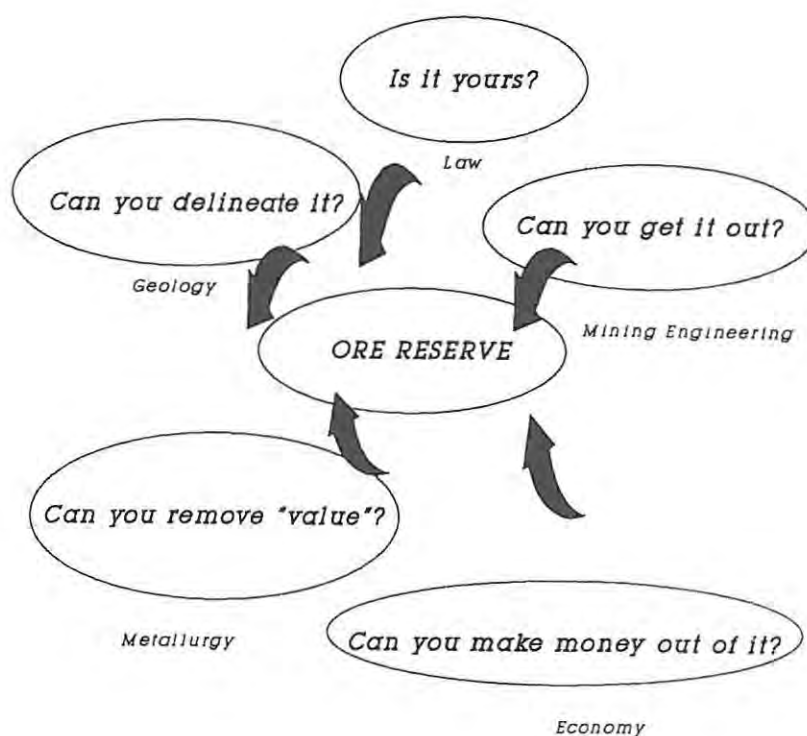


Fig 5.1 Some questions that arise in assessing an ore reserve estimation and different disciplines related to them.

The economic margin estimate is most often the product of team effort. In this team, the geologist is the most informed about the mineralized body. He has gathered the basic data and interpreted the geological model, and indeed in the predevelopment stage of the mining project, is normally the only person who has actually seen the minerals from which the "**profitable**" metals are to be extracted. It is thus the geologist's responsibility to define and describe the mineralized body as accurately and efficiently as possible. The ore definition should be of the broadest geological basis, taking into account those geological factors that could affect the mining, the metallurgical process, and therefore the economic viability of the deposit.

The question **Can you delineate it?** (Fig 5.1) was answered as far as possible in the previous section A by the description and interpretation of the mineralized body. The remaining questions involved in the ore reserve represent different disciplines that are beyond of the scope of this dissertation.

The final aim of any mining activity is profit and therefore in the question **Can you make money out of it?** lies the transition between a **mineralized body** and an **ore body**.

As will be discussed in the next chapter, the concept of "**profit**" is implicit in the definition of an ore reserve. The flexible concept "**economic**" rather than profit is considered more appropriate. This allows different economic considerations to be taken into account when determining what ore is to be defined as at the feasibility study stage.

Economic factors which are highly variable and beyond a mining enterprise's control affect the economic exploitation of a mineral resource. A good understanding of the mineral economic issues inevitably requires a broad understanding of the forces which act on the markets for mineral products to establish supply, demand and price conditions.

On the basis of the foregoing discussion this section begins with an outline of the iron market conditions in the form of a commodity analysis.

5.1 Commodity Analysis

As was mentioned previously, at the first stage of the evaluation process a complete commodity analysis should be undertaken. This analysis includes general topics such as world resources distribution as well as detailed information such as mining costs for specific mines (Table 5.1).

Table 5.1 Commodity analysis

<i>RESOURCES</i>	<i>LOCATION</i>
<i>SUPPLY</i>	<i>ADEQUACY OF RESOURCES</i>
<i>DEMAND</i>	<i>MAIN PRODUCERS</i>
<i>USES</i>	<i>FORECAST TRENDS</i>
<i>PRICE</i>	<i>DEMAND PATTERNS</i>
<i>GRADE</i>	<i>TRENDS</i>
<i>RESERVES</i>	<i>OVERALL OUTLOOK</i>
<i>COSTS</i>	<i>TYPICAL EXAMPLES</i>
	<i>FIGURES FOR PROFITABLE MINES</i>
	<i>COST AND PROFITABILITY OF TYPICAL MINES</i>
	<i>DESIRABILITY OF LOOKING FOR MORE RESOURCES</i>
<i>EXPLORATION</i>	<i>RECOMMENDATIONS: TARGET AREAS GEOLOGICAL SETTINGS</i>

Resources

World resources of cheaply mineable iron ore are abundant. The total world resources have been estimated at 96600Mt (Minerals Bureau estimates, in Smith, 1991). South Africa's reserves are estimated at 6000Mt, representing about 9% of Western and 6% of world resources (Fig 5.2).

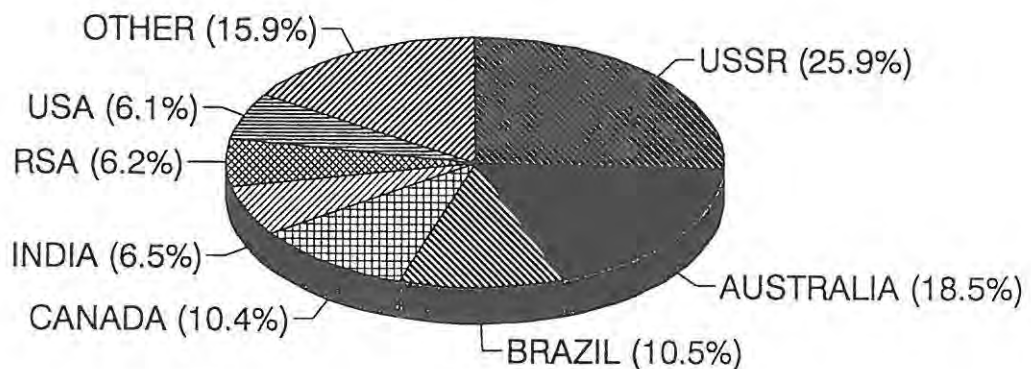


Fig 5.2 World reserves of iron ore (after Grohmann, 1989)

Iron ore resources are well distributed throughout all the continents, as can be seen from figure 5.2. A large percentage of resources are concentrated in the former Soviet Union (Eastern Europe). Australia is also an important source of reserves. In South America, Brazil is probably underestimated in Fig 5.2, taking into account the new discoveries in the Carajás district.

South Africa's resources are principally contained in the banded iron formations, and the main deposits are located in the Sishen - Postmasberg area where large, irregular bodies of hematite ore occur. High-grade hematite deposits are also associated with the iron formations of the

Chuniespoort Group at Thabazimbi, with reserves estimated at 100Mt (Taylor et al., 1988). Extensive reserves of magnetite are located in the magnetite seams of the Bushveld Igneous complex. Beach and sand deposits occur along the Natal coast containing ilmenite with an average of 36.8% iron and 31.6% titanium.

Supply

The main world suppliers of iron ore are the former-U.S.S.R., China, Brazil and Australia. South Africa holds seventh position and had the most positive percentage increment during the last five years of the 1980s (Fig 5.3).

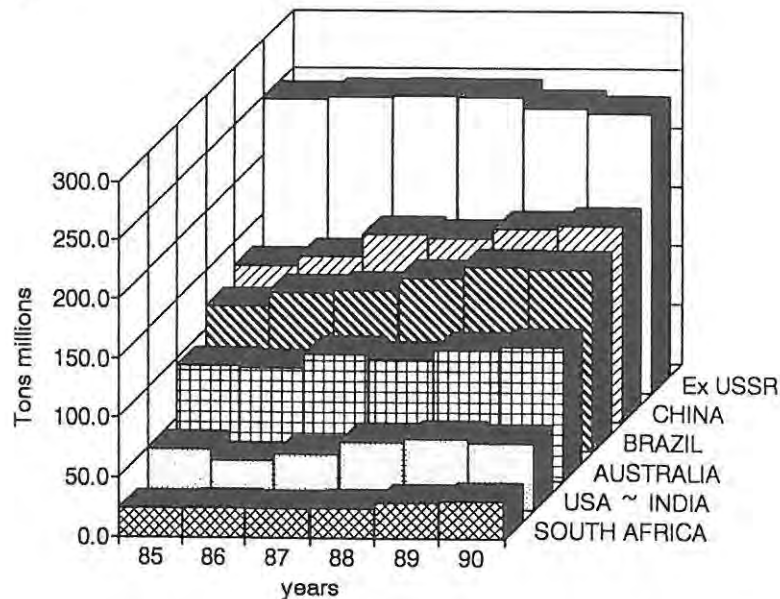


Fig 5.3 World iron ore production (Tons millions) (after Smith, 1991)

An important change in the location of the world's steel production occurred between 1955 and 1984, shifting from the USA as the main producer to communist countries by 1984 (Taylor et al., 1988). In a matter of ten years, over 600 steel making facilities in the USA were closed. This shift in world production of iron ore is attributed to substitution of alternative materials and saturation of demand in the developed countries amongst others (Taylor et al., op cit). According to

the Taylor et al., an oversupply situation has been forecast for the present decade (Taylor et al., 1988). Nevertheless, world production and trade in iron ore reached record levels in 1989, with a total output of 982Mt, of which some 422Mt were traded internationally. At the beginning of 1991, stock piles of iron ore were generally depleted.

In order to have a proper understanding of the supply situation and to perform some forecasting for the coming five years, the main suppliers are briefly analyzed in the context of the present political situation (1991-1992).

Analysis of the main suppliers

Sources in the former **Soviet Union** indicated that iron ore production has declined over the past 15 to 20 years, largely due to the increased depths of open-pits and associated complex mining conditions. About 30% of the open-pit mines operate at depths of 300m.

Deliveries of iron concentrates were delayed, during the first half of 1989 because of shortages of rolling stock, partly caused by a series of railroad workers' strikes. The economic situation in the U.S.S.R. in 1990 deteriorated significantly and the crisis began to grow, encompassing all phases of the economy.

Iron ore production in the former Soviet Union fell by 13% in the first nine months of 1991. The steel industry is in crisis because of years of under-investment, the current political upheaval and the major coal industry strike which took place earlier in 1991 (Mining Journal, Nov 29, 1991).

The second main iron ore producer is **China**. After the isolation imposed following the Tiananmen Square incident, the sanctions imposed by Western countries have gradually been relaxed. During 1990, China experienced a labour oversupply, far exceeding anticipated demand. Chinese raw steel production rose by 9.7% above that of 1989 to 67.2Mt

in 1990. The increase in production is in line with the Ministry of Metallurgical Industry (MMI) three-stage development plan for the industry in the 1990's:

- i) Low-cost modernisation by introducing new production and **management techniques** and by adopting provisions to make **extensive use of computer hardware and software.**
- ii) Importing foreign equipment to modernise plants.
- iii) The third stage is to construct several large plants on greenfield sites.

The Ministry of Metallurgical Industry has requested assistance from Japan's iron and steel sector. During 1991 China produced 33.6Mt of steel in the first half of the year, an increase of 4% on the corresponding period in 1990. The output value of the large and medium-sized iron and steel enterprises is estimated to have reached Y43,600 million (about \$US 10,000 million) in the first five months of 1991 (Mining Journal, July, 1991).

During the last few years **Brazil** has been the world's biggest exporter of iron ore, the total production during 1990 was estimated to be 152Mt. The output of the Companhia Vale do Rio Doce (CVRD), the world's largest producer of iron ore, was 86Mt, of which 55Mt from the company's southern division mines in Minas Gerais and 31Mt came from its northern, Carajás mine in Pará (Metals & Minerals Annual Review, 1990). Iron ore exports achieved a record high level for the third consecutive year. With its future plans, the second largest iron producer, Mineracões Brasileiras Reunidas (MBR), will be able to produce 35Mt/y, which is equivalent to the present capacity of CVRD's huge Carajás mine (Metals & Minerals Annual Review, 1991). The identified ore resources of the Carajás region are reported to be about 18 billion metric tons, containing 65 percent Fe (Machamer et al., 1991). In economic terms, the district ranks with the Witwatersrand as one of the world's truly great mineral districts (Table 5.2). According to these facts, Brazilian iron ore production for the next decade can be optimistically visualised throughout the next decade.

Table 5.2 Comparative Ranking of Some Major Iron ore Regions
(Machamer, et al. 1991)

Region	Metric tons
Greater Carajas region (geologic reserves with >60 % Fe ¹)	10.9 x 10 ⁹
Minas Gerais, Brazil (geologic reserves ^{1,2})	17.1 x 10 ⁹
Hammersley Ranges, Australia (demonstrated economic resources with >50% Fe ³)	14.6 x 10 ⁹
Lake Superior region, United States (cumulative ore and pellet shipments ⁴)	5.1 x 10 ⁹
Krivoi Rog district, former USSR (cumulative shipments ⁵)	3.7 x 10 ⁹
<p>1 Data from Companhia Vale do Rio Doce</p> <p>2 Include only those resources controlled by Companhia Vale do Rio Doce</p> <p>3 Bureau of Mineral Resources, Canberra</p> <p>4 Minnesota Mining Directory and America Iron Ore Association</p> <p>5 Informal approximation prepared with the assistance of U.S. Bureau of Mines</p>	

Australia, together with China and South Africa, is one of the countries which experienced a positive production increment between 1989 and 1990 (Fig 2.2). During the last few years, the mining industry in Australia has gone through a time of prosperity, with increased production, sales and profit.

The biggest producer in the Pilbara district of Western Australia is CRAIS Hammersley Iron which, in 1990, shipped 49.9Mt, 8Mt more than in 1988. The new production and productivity records are the result of company reorganisation. Only four years ago, production was 30.2Mt with a 25% larger work-force. Hammersley has now started production at the Channar orebody which is a joint venture between Hamersley (60%) and China Metallurgical Import and Export Co.

The second biggest producer in the Pilbara district is BHP, whose Mount Newman mine in 1990 produced 31.7Mt. The mine's reserves are 1,200Mt, including 950Mt of ore grading 64.4%Fe.

Despite some mining development problems, Australia looks set to increase supplies in the next few years.

South Africa in the supply environment

South Africa is ranked as one of the top ten world iron ore suppliers (Fig 5.2). The largest South African producer and principal supplier of iron ore to the export market is Iscor's Sishen Mine. Iscor also operates **Thabazimbi** Mine in the Northern Transvaal, where the Kwaggashoek East deposit analyzed in this thesis is located (Fig 2.4, chapter II).

Of the 30Mt of iron ore produced in South Africa in 1990, some 17Mt (57%) was exported. This was a 17.2 percent increase on the 1989 figure of 14.5Mt. After three years of gradually increasing production up to 1990, output of iron ore in South Africa was about 4% less in 1991.

At the end of 1991, Iscor Ltd. signed a five-year contract to supply 20Mt of ore to six Japanese steel makers in a deal worth more than R1,000 million. Under the terms of this agreement, Iscor will supply 4Mt of iron ore annually from its Sishen mine in the north eastern Cape Province over the next five years. The announcement was made after Japan removed all economic sanctions against South Africa. Although South African iron ore had never been officially subject to sanctions by the Japanese, the six companies involved had not renewed contracts with Iscor since 1988 when a 12-year deal expired (Mining Journal, Oct 25, 1991).

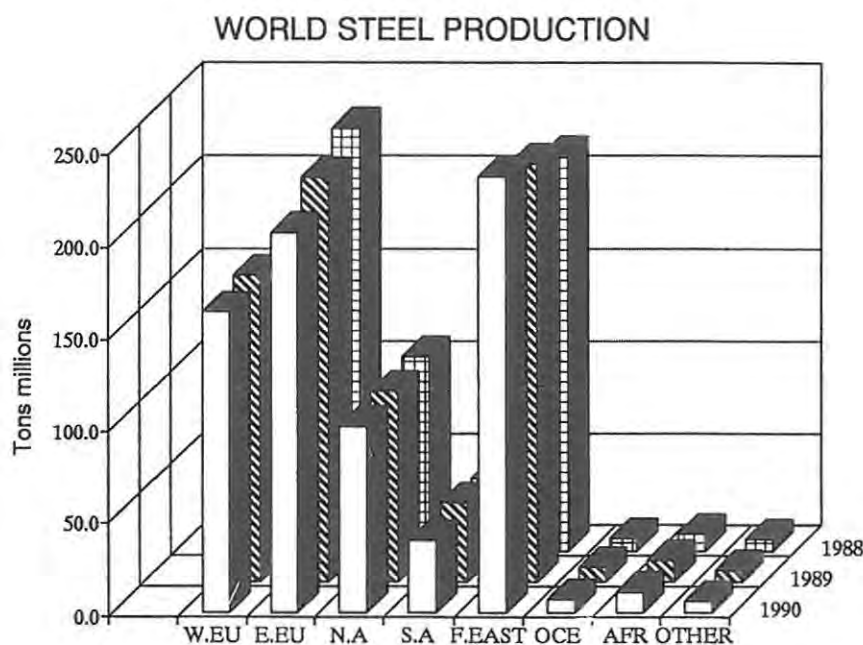
With the lifting of sanctions and the possibility that South Africa may export more steel, iron ore available for export could be in short supply.

Demand and Uses

The overall demand for iron ore is very closely if not entirely linked to the world demand for steel. Japan is the largest market economy steel maker, yet it has no meaningful domestic resources of iron ore.

Demand is largely dictated by the level of international economic activity and by the close relationship between changes in steel use and growth of a country's gross domestic product. A further pertinent macro-factor is the change in intensity of steel usage that may be observed as a country passes through the economic stages from industrial underdevelopment to high rate development and, finally, to industrial maturity.

The recessionary phase of the world economy in 1990 ended the steady rise in steel output during the 1980s (Fig 5.4). However, Japanese stainless-steel production, which was depressed at the beginning of 1990, experienced growth in early 1991. This bodes well for South African ferrochrome producers. In October 1991 there was a short supply in Japan's stocks of ferrochrome because the Japanese stainless-steel industry was operating at record levels.



*Fig 5.4 World Steel Production (tons millions)
(After Smith, 1991)*

The reason for the good performance of stainless-steel as compared to the carbon-steel industry is substitution. Japan is leading a current world trend to substitute stainless-steel for many traditional carbon-steel applications, notably in the construction and transport industries (Grohmann, 1991).

From South Africa's point of view, with its main markets for both steel and iron ore in Japan, Taiwan, the EEC and USA, the position is stable at lower levels in terms of sales of steel and ore. In 1989, demand for Highveld Steel's and Iscor's output was good and both companies had excellent results for 1988/89. Profitability in 1990 and again in 1991 has been much reduced.

A forecast of steel output up to 1996 was done in a recent study (Drew Shipping Consultants, Ltd., 1991) showing relatively steady conditions (Table 5.3).

*Table 5.3 Forecast for steel output
(Mining Journal, Nov, 1991)*

	--Forecasts (Mt)--			
	1990	1992	1994	1996
Steel Output				
E.C	136.8	137.4	134.3	129.3
North America	101.2	94.5	97.3	93.8
Japan	110.3	111.2	106.8	103.1
Others	<u>421.7</u>	<u>407.9</u>	<u>428.9</u>	<u>440.3</u>
World	770.0	751.0	767.3	766.5
Seaborne Trade				
Iron Ore	354.2	358.6	366.2	372.6
Coking Coal	161.9	166.4	168.8	170.2

It is not easy to make any reliable forecasts for steel production in the current circumstances for the former Soviet Union, but Soviet sources expect the down-trend to continue (Mining Journal, Nov, 1991).

Prices

Iron is sold on the world market in different forms: as lumpy ore, fines, directly reduced ore and as pellets. Prices in US dollars increased between 1983 and 1990.

Since 1983, the local price for South African ore in R/ton terms have been increasing (Fig 5.5), but the oversupply situation, generated particularly by developing countries such as Brazil, meant that prices in early 1987 were lower than in 1983, in dollar terms (Smith, 1991).

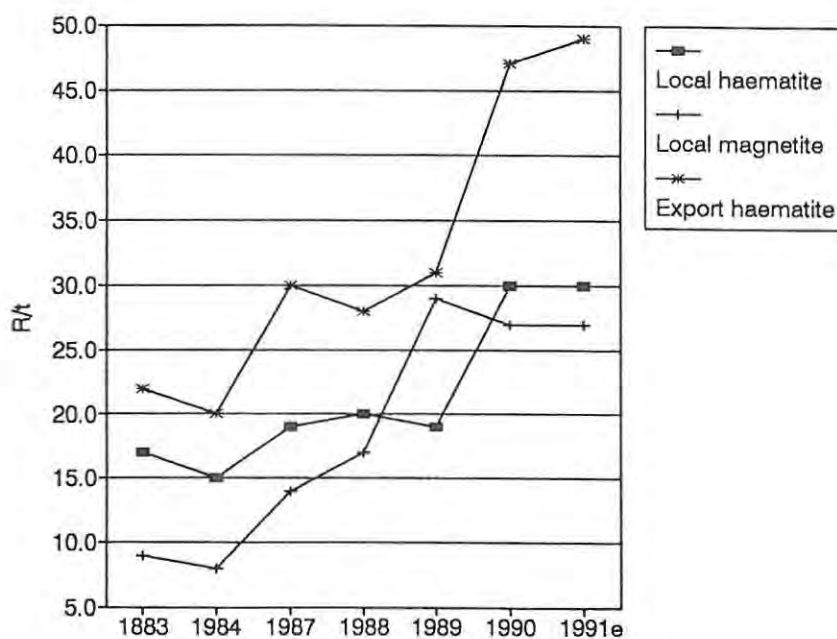


Fig 5.5 Iron ore prices in South Africa R/t

During the past year, export prices improved owing to strong demand due to Liberian and Eastern European supply failures. The lower \$/R exchange rate also contributed to good export ore prices during 1990. During 1991, iron ore, hematite and magnetite prices experienced a slight increment

from May to July (Table 5.4) (Mining Mirror Vol no 4-6,1991) probably due to the uncertain political situation in the former Soviet Union.

During February 1991, Japanese furnace steelmakers and Iscor negotiated sales contracts for iron ore, estimated to total 4.8Mt in volume over the following twelve months. Prices agreed show an increase in relation to the previous year. This increment may be the result of a current world short supply position and efforts by producers of iron ore to regain an equitable price for this product (Nell, 1991b). The rates of increase appear to be in line with those agreed to by producers elsewhere in the world who sell to Japan (Fig 5.6).

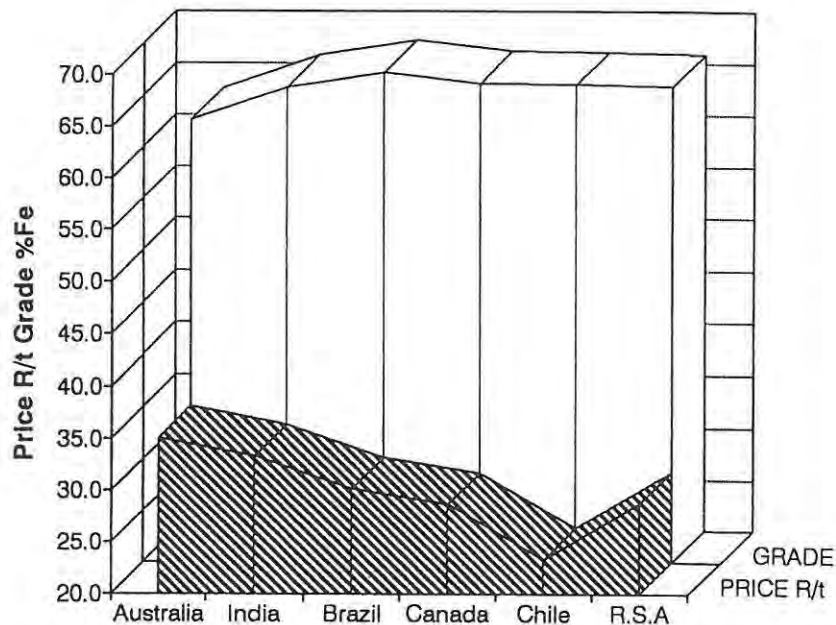


Figure 5.6 Prices agreed by producers who sell to Japan

Despite little difference between the Brazilian and South African steel prices, Brazil takes advantage of the political restrictions within the African continent on South African steel and sells to African countries such as Nigeria, Cameroon, Congo, Ghana, Guinea, Gabon, Zaire and Madagascar.

Mine grade and reserves

A comparative ranking taking, into account reserves and grade of some of the major iron regions, is shown in table 5.2 (supply section). According to this, the Greater Carajás region has about 18 billion metric tons exceeding 60%Fe (Machamer, et al.,1991).

The biggest iron ore mine operating in South Africa is Sishen with 1410 Mt in situ reserves with Fe > 60% (Taylor et al., 1988). However, the tendency to replace ore reserves mined by ongoing exploration is expected to continue for at least the next five years (Taylor et al., op cit.).

In Sishen, 1180Mt can be mined by open pit methods, making the mining cost cheaper, but the need for beneficiation in order to supply a product of acceptable and constant quality to blast furnaces is a problem. Thabazimbi's ore reserves are 100Mt at 63% Fe, about 60 percent of which can be mined by open pit methods (Taylor et al., op cit.).

According to market conditions, a competitive deposit would, in addition to having large, cheaply mineable reserves (100s of millions of tons), have to meet certain quality specifications (Table 5.5) (Smith, 1991). This means that hematite ore with less than about 60% Fe would not be attractive.

Table 5.5 Ore specifications for iron ore product.
(Modified from Smith, 1991 and Iscor internal report: Thabazimbi)

	Sishen	Thabazimbi	
		Lump Ore	Fine Ore
Fe	68-66	63	63
SiO ₂	4-1.5	6.0	4.5
Al ₂ O ₃	1.3	1.0	1.3
P	trace	0.05 max	0.06 max
MnO	trace - 1.5	0.4	0.5
K ₂ O		0.09	0.09
S	trace		

Mining costs for iron ores have to be held at "rock bottom". Open cast mining is virtually essential to achieve this requirement

The export specifications for iron ores are quite strict in relation to deleterious elements such as phosphorus and sulphur that dull the steel making process. Therefore it is important that the distribution of the deleterious elements in the ore body be well established in order to facilitate blending and selective mining.

Commodity analysis conclusions.

Iron ore resources are distributed world wide. Supply-demand is expected to be balanced for the next five years. The influence of political and economic factors can be seen in the former Soviet Union's drop in output. On the other hand, countries with proper development plans, open to modernisation in management techniques and with new equipment have increased production levels during the past few years (e.g. China, Australia). Despite the continued recession in the USA steel industry, Japan continues to be the largest market economy country steel maker and has signed agreements with its normal suppliers including South Africa. Prices are expected to improve slightly if supplies from Liberia and Eastern Europe continue to decline.

Distribution of deleterious elements such as P, K_2O and S, should be determined in the geological model of the deposit in order to facilitate optimum extraction of the ore and to meet quality specifications.

To hold mining costs to a minimum, open cast mining is virtually essential. The necessity to reappraise economic factors during the life of a mine in order to maximise the economic surplus and to minimise the wastage of natural, economic and human resources is imminent.

VI ORE RESERVE ESTIMATION

6.1 Introduction

The trend in recent years seems to have been to broaden the concept of ore reserve estimation from its traditional computational basis, to an approach embracing all the many factors that can affect the expectation and realisation of recoverable metal or other products from a mine (Bujtor and McMahon, 1983). Ore reserve estimation is not just a calculation; in fact the calculation itself is the least important part of the whole process. With new computational techniques, these calculations can be performed very fast as often as is required, but the most sophisticated techniques of calculation do not improve the accuracy of the ore reserve estimation (see Subsection 6.7 Estimation methods).

Ore reserve estimation is based on samples. They are the nerves of a mining operation (Lane, 1988). Mineralized bodies cannot be sampled to such an extent as to eliminate margins of uncertainty in the geological interpretation. Ore bodies are geological phenomena; ore reserve estimates of them are as reliable and accurate as is the geological data and its interpretation.

The reliability of the ore reserve estimate varies progressively through time as more and more information becomes available. The lowest order of reliability of estimation exists at the time of discovery. The maximum level of certainty concerning the ore reserves within a deposit is reached when the deposit is completely mined out. Between these two extremes are variable levels of certainty as to the tonnage and the grade of the resource (Readdy et al., 1982).

A good understanding of the geology of the deposit is a fundamental step before any ore reserve calculation can be made. Uncertainties about the geological interpretation might be reflected in some way in the diverse categories of ore identified for medium and long term planning purposes. These uncertainties need not be only a margin of error. A completed

assessment of ore reserve estimation should include an optimistic and a pessimistic point of view, including the minimum and maximum tonnage and grade that can be expected at least for medium term planning (probable ore) and the positive and negative factors affecting these estimates.

An important aspect to be considered before examining the factors affecting ore reserve estimation is the need to define what is meant by the terms involved in this operation. The definition of the terms **ore**, and **reserve** and the methods and criteria for their estimation will be discussed in the first part of this chapter.

6.2 Ore definition

A common definition of ore is " a naturally occurring material from which a mineral or minerals of **economic value** can be extracted at a **reasonable profit** " (Bates and Jackson, 1980). There are two important factors implicit in this definition: a) the economic connotation, which determines the margins of the ore zone, and b) the extractability of the minerals which is constrained by physical and mining parameters amongst others.

According to this definition, "the natural minerals" remain the same, or at least change only slightly in historical time. The flexibility of the concept lies in the economic and operational factors rather than in the geological aspects.

The idea of the stability of the mineral occurrence is well expressed by King et al.(1982): "Of all the aspects of a mining operation, the ore deposit and its characteristics are alone in being unalterable. Any changes in our expectations are only changes in our knowledge or understanding. In all other directions, mistakes, miscalculations or misunderstandings are amenable to rectification if there is the need and the justification, but the ore deposit and its characteristics are beyond human modification".

The need for a concept based mainly on geological principles, led to the use of **mineralized body** instead of **ore body** in the first section of this dissertation. Compared to a ranking of terms that has been suggested by Taylor (1991) (Table 6.1), the term mineralized body used here, is equivalent to the term **ore-rock** described by the above-mentioned author.

Table 6.1 Ranking of mineral terms, arranged in order of increasing precision, compared with the terms used in this thesis (Modified from Taylor, 1991).

		This thesis
Orebody (Obviously useful)	A combined tonnage and grade of ore that, for any reason, will justify commencing or continuing active production	ore body Fe>55% SiO ₂ <15% Talc, carbonate <20%
Ore (probably useful)	Ore-rock of quantity and grade that justifies continuing study, with a view to either future or continued mining	
Ore-rock (uncertain, some may be useful)	Rock containing useful constituents, in quantity or concentration sufficient to encourage preliminary investigation and measurements	mineralized body Fe> 45%
Waste (obviously useless)	Rock that is obviously valueless, except possibly as a by-product	BIF, (Fe 20 - 45%)
Rock	Solid mineral	Dolerite, shale, dolomite, diabase.
Mineral	An element, compound or material that is generally neither animal nor vegetable (which thus comprises almost the entire mantle of the earth, whether solid, liquid or gas)	
Material	Almost everything	

The term ore-rock describes a rock containing useful constituents in quantity or concentration sufficient to encourage preliminary investigation and measurements. Its equivalent (mineralized body) in the first section of this thesis, has been used to define the envelope within

which the ore body lies. The minimum iron content for this envelope is 45% Fe, taking into account that the banded iron formations or protore average of iron is 39% in this mining area.

It is at this level (ore-rock or mineralized body) that the ore reserve estimate is performed and geostatistical methods may be applied (Taylor, 1991).

An important break is pointed out by Taylor (1991) between the static concept of a mineable reserve (ore, probably useful), almost unchanged over recent geological time, and the dynamic proposal to do something with it within a human time scale (ore body, obviously useful) (Table 6.1).

The linkage of the static definitions of qualities and quantities as ore-rock or mineralized body to a dynamic concept '**profit**' that turns them to an ore body, is problematic.

A further complication is that the term 'profit' is not linked worldwide with the ore body concept in the same way. In socialist economics, "**ore**" is often defined as mineral material that can be mined for the **benefit of mankind** (Kwzvalt, M and Böhmer, M., 1968).

The suggestion of a flexible concept of "economic" instead of "profit" (Comanos, G., 1979) is accepted. The term 'profit' when used in the definition of 'ore' is not sufficiently flexible to take into account changing or different circumstances. The **economic ore** at the point of mine closure differs from the premining **economic ore**. When a mine cannot operate to yield a positive cash flow, the question of mine closure inevitably arises. Quite often the negative cash flow may be for a short, or limited period. The mine should continue to operate for that period, provided that it is more economic to do so than to close down. That is to say, provided the cash flow from continuing to operate is greater than the cash flow which would result from closing or closing and reopening (Comanos, op. cit.).

On the other hand, Lane (1988) presents an economist's viewpoint in suggesting that the economic definition of ore should be that definition which maximizes the Net Present Values of a mining operation. According to him, material from the mineralized body should be scheduled for mining as **ore** if, and only if, the decision to treat it adds to the overall economic value of the operation.

No economic estimate is likely to be valid for a long period of time. Technological changes, changes in transportation, accessibility or rates and changes in political factors, to name just a few, cause a constant juggling of relative economic standings (Ohle, 1972).

The economic analysis of operating strategies for mines differs from other industrial or commercial undertakings because it deals with **finite resources**. Depletion and Present Value are critical and essential factors in the analysis of a cut-off grade strategy, the cut-off being the economic boundary of the mineralized body which can turn this material into ore and maximize benefit.

The Thabazimbi concept of ore

The Kwaggashoek-East deposit works according to the Thabazimbi concept of ore. Two main kinds of ore were distinguished at the end of the exploration phase, when the ore reserve estimation was performed (Standard Practice Instruction, 1990. B1812-A, Iscor TBZ.). They are the following:

High grade ore (E) defined as a rock essentially mesobanded constituted of primary iron minerals, mixed with a mesobanded rock of secondary minerals. The geochemical values are Fe > 60%, and SiO₂ < 15%.

Low grade ore (LAE) is a mesobanded type of rock formed by iron minerals, mixed with secondary mesobands of ferruginous chert and/or calcite and/or talc. The rock has, in total, between 55% and 59.9% Fe and a contamination (chert, calcite, and/or talc) of less than 20%.

The Thabazimbi ore concepts have, with only slight changes, been successfully used in the Thabazimbi district during the last few years, although there is a lack of the background geological knowledge normally used in this mining center reflected in these definitions.

More than 70 geological codes (Appendix 6.1) are used to describe different parameters when logging the cores. These codes represent the description of structure, texture, rock quality, colour and grade of weathering, amongst others, for samples of diamond and percussion drillholes. Beside this, a mineral-chemical classification in relation to the deleterious elements (Appendix 6.2) is performed.

All this geological data should improve knowledge of the ore quality and probably broaden the definitions in particular circumstances.

6.3 Reserve definition and different categories

The terms **resource** and **reserve** are always subject to confusion and the terminology differs depending on the mine center and the country where it is used. As yet, there is no internationally accepted code for reserve classification. Various terms are used to describe and classify mineral resources, some of which have gained wide use and acceptance although they are not always used with precisely the same meaning (Appendix 6.3 and 6.4).

A proper nomenclature or resource classification system should be workable in practice and useful in long-term planning. Commercial planning must be based on the probability of discovering new deposits, on developing economic extraction processes for currently unworkable deposits, and on knowing which resources are immediately available. Thus resources must be continuously reassessed in the light of new geologic knowledge, of progress in science and technology and slight changes in economic and political conditions. To best serve these planning needs, known resources should be classified from two stand points:

1. purely geological or physical/chemical characteristics - such as grade, quality, tonnage, thickness and depth of the material in place, and
2. profitability analyses based on costs of extracting and marketing the material in a given economy at a given time.

The former constitutes important, objective, scientific information on the resource and a relatively unchanging foundation upon which the latter more variable economic delineation can be used.

The Australasian Institute of Mining and Metallurgy (1988) and the Australian Mining Industry Council (1987) classification (Fig. 6.1) (Appendix 6.4) seems to meet the needs outlined in the foregoing discussion. In this classification, the term **resources** is used as an **in situ** mineral occurrence quantified on the basis of geological data and a geological cut-off grade only. The resources are divided into three categories: inferred, indicated and measured.

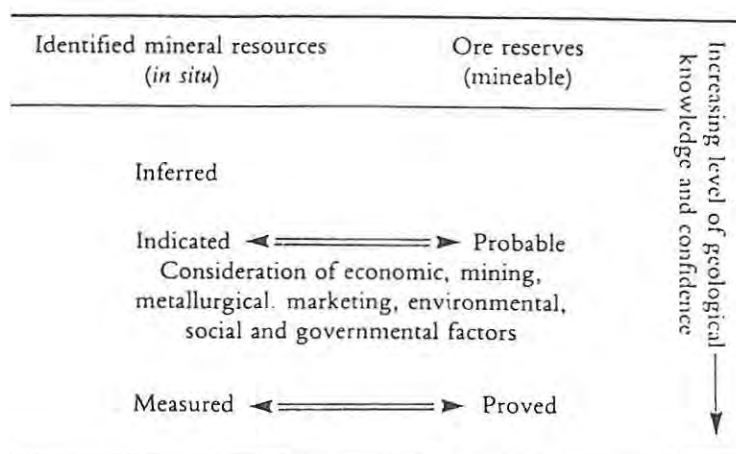


Fig. 6.1 AIMM/AMIC Classification of identified mineral resources and reserves

The term '**ore-reserve**' means that part of a measured or indicated resource, which could be mined including dilution and from which valuable or useful minerals could be recovered economically under conditions realistically assumed at the time of reporting. The flexibility of this definition and the clarity of the distribution between the geological and economic connotations, besides its location in a time scale, meets the needs discussed previously.

Table 6.2 summarizes a comparison between the classification system used by the US Bureau of Mines (USBM) and US Geological Survey (USGS)(1980) with the Australasian AImm/AMIC classification (1989) and the Thabazimbi classification at the time of the exploration phase of the Kwaggashoek East deposit (1989). The categories of **proved** and **probable** of the IMM/AMIC are '**ore reserves**' and therefore their economic connotations lie in the definition of this term mentioned before.

The Thabazimbi ore reserve classification is closer to the USBM categories. The term "**probable**" is used normally for medium term planning purposes. Kwaggashoek East ore reserves, at the end of the exploration phase, were classified in this category. According to the Thabazimbi classification the category "probable" means that there is **enough information** as regards the orebody outlines. It can be used for mine planning, but the risk of deviation or variation of the different kinds of ore and uncertainty about the orebody is about 25%. The information sufficient for this category is in direct relation to the sample pattern used for the project. Sampling is the basis of any ore reserve estimation and the adequacy of the sample method used and its density depends on the kind of deposit surveyed.

6.4 Sampling

Sampling of an ore deposit is a process of approximation. The objective is to arrive at an average value for the samples which most closely represents the true average value for the body in question.

Table 6.2 Comparison of various reserve - resources categories used by the USBM/USGS, Australasian IMM/AMIC and the Thabazimbi mine district

USBM / USGS	Australasian IMM/AMIC		Thabazimbi classification	
<p>Measured ore (proved) is ore for which tonnage is computed from dimensions revealed in outcrops, trenches, workings and drill-holes and for which the grade is computed from the results of detailed sampling. The sites for inspection, sampling and measurement are so closely spaced and the geological character is so well defined that the size, shape and mineral content are well established. The computed tonnage and grade are judged to be accurate within limits which are stated, and no such limit is judged to differ from the computed tonnage or grade by more than 20%.</p>	<p>Proved. These are reserves stated in terms of mineable tonnes/volumes and grades in which the identified <u>in situ</u> resource has been defined in three dimensions by excavation or drilling, and should include additional minor extensions beyond actual openings and drill-holes, where the geological factors that limit the orebody are known with sufficient confidence, that it is categorized as a 'measured resource'</p>	<p>O R E R E S E R V E S</p>	<p>Proven: This is an ore reserve which is based on through geological information (mapping, drilling, sampling) reflecting accurate information regarding the quantity, quality and out lines of the ore reserve. The margin of error associated with the ore definition and extent of the reserve is <u>+</u> 15%.</p>	
<p>Indicated ore (probable) is ore for which tonnage and grade are computed partly from specific measurements, samples or production data and partly from projection for a reasonable distance on geological evidence. The sites available for inspection, measurement and sampling are too widely or otherwise inappropriately spaced to outline the ore completely or to establish its grade throughout.</p>	<p>Probable. These reserves are stated in terms of mineable tonnes/volumes and grades where the conditions are such that ore will probably be confirmed but where the <u>in situ</u> identified resource has been categorized as 'indicated' and has not been defined with the precision necessary for the 'measured' category. Probable ore-reserves include ore that has been sampled on a pattern too widely spaced to ensure continuity</p> <p>Indicated. These are sampled by drill-holes, underground openings, or other samplings procedures at locations too widely spaced to ensure continuity but close enough to give a reasonable indication of continuity and where geoscientific data are known with a reasonable level of reliability.</p>		<p>R E S O U R C E S</p>	<p>Probable reserve: This is an ore reserve which is based on sufficient information regarding the outbody for mine planning purposes where the risk of anomalies regarding the quality and extent of the orebody is greater than for proven ore. The margin of error associated with the ore definition and extent of the reserve is <u>+</u> 25%.</p>
<p>Inferred ore (possible) is ore for which quantitative estimates are based largely on broad knowledge of the geological character of the deposit and for which there are few, if any, samples or measurements. The estimates are based on an assumed continuity or repetition for which there is geological evidence; this evidence may include comparison with deposits of similar type. Bodies that are completely concealed may be included if there is specific geological evidence of their presence. Estimates of inferred ore should include a statement of the special limits within which the inferred ore may lie.</p>	<p>Inferred. This is an estimate, inferred from geoscientific evidence, drill-holes, underground openings, or other samplings procedures and before testing and sampling information is sufficient to allow a more reliable and systematic estimation.</p>			

The sampling of metalliferous mineral deposits in an exploration phase is largely confined to the analysis of drill cuttings, or cores, and is aimed at the evaluation of individual, often widely spaced, intersections of the deposit. The mode of occurrence and morphology of a mineral deposit has considerable impact on the type and density of sampling, and on the amount of material required. Homogeneity and continuity of the mineralized body determine the grid pattern of samples.

A clear relationship between the proportion of minerals and their homogeneity is given by King et al. (Fig. 6.2). Bedded iron ranks third in ease of estimation. It has a high proportion of ore mineral and is generally very homogeneous.

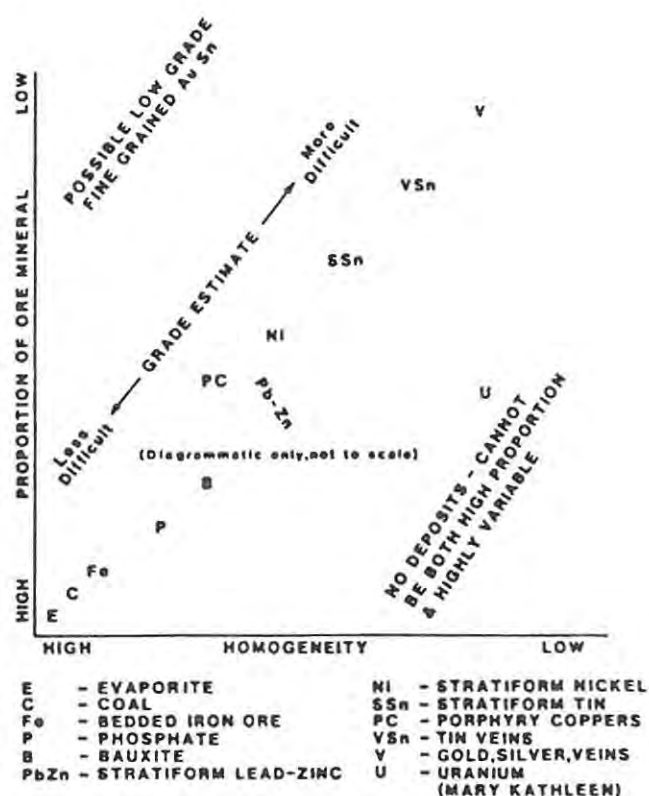


Fig. 6.2 Proportion of ore mineral versus homogeneity (for equal size samples) (King et al., 1982)

According to a characterization of universal deposits for sampling purposes, the Kwaggashoek East body is in the category of stratiform deposits (Annels, 1991). These are deposits which lie within a

particular lithological unit or lithofacies and whose contained ore minerals are largely controlled by bedding and other sedimentary features.

Table 6.3 compares their significant features, from the point of view of sampling, with Kwaggashoek East general features.

As Kwaggashoek East forms part of a chain of deposits located in the same range (Fig. 2.4. Chapter II), its exploration model was clear enough to justify a wide drilling pattern to determine the outlines of the mineralized body. A follow-up drilling campaign was completed to determine the continuity and grade of the body. In an area 900m * 400m, an irregular grid of 66 boreholes was distributed with a spacing of 50m along strike and 40m to 70m along the dip of the bedding.

Nearly 80% of the boreholes were of the percussion type. Twenty percent of them switched to diamond drill when the ore was intersected. Most of the boreholes were surveyed at 8m intervals using a Sperry Sun Instrument. The borehole traces show a tendency to deviate perpendicular to the bedding. Deviations of about 20m from the original surveyed angle were detected in boreholes with a length of 250m.

A major disadvantage of percussion drilling is that samples cannot be taken accurately with respect to geological boundaries. Consequently this method of sampling can best be used where the sample lengths are small with respect to the separation of the geological limits of the mineralization. In Kwaggashoek East, samples were collected at constant one meter intervals down the length of the core, although samples were taken at shorter intervals according to geological contacts when necessary.

The adequacy of sampling in Kwaggashoek East seems to meet the conditions for the given category (probable). The sample grid is considered adequate to define the orebody outlines, the continuity and homogeneity of the body.

Table 6.3 Comparison between the significant features for sampling purposes of a stratiform deposit and Kwaggashoek East.

Stratiform deposits	Kwaggashoek East
1. They tend to be thick (i.e. up to 20m)	Average thickness 30m
2. They have a large areal extent	More or less 600m * 250m
3. They are commonly either gently inclined or higher folded and tectonized, thus presenting problems for sampling and evaluation	Average dip 45° South
4. Grades are uniform and predictable, except when affected by late stage remobilization, metamorphism or veining.	Secondary processes affect the uniformity of grade
5. Gradual and systematic lateral changes in grade allow a wide sampling interval.	Lateral changes in grade are within 15m and 25m
6. Being hosted by meta-sediments they tend to be easier to sample and less prone to bias from variable sample size, rock hardness or high Nugget effect (high grade patches)	In a vertical direction, there is small Nugget effect
7. Many have a moderately high grade and thus sampling errors are less significant	Grade between 55% and 65% Fe
8. Assay cut-offs may be gradational, especially at the hangingwall and difficult to pin-point underground, so that more samples are needed to ensure that the complete ore size is covered.	The hangingwall is a gradational contact with banded iron formations

6.5 Grade

The grade of a mineral deposit is determined by the effectiveness of an ore forming process, which is the interaction between an ore forming mechanism and the environment in which it operates (Esterhuizen, 1983).

The term 'grade' is defined as a relative quantity or the percentage of ore-mineral content in an orebody (Bates and Jackson, 1980). Another definition states that it is the concentration of a metal in an orebody, usually expressed as a percentage or in parts per million (ppm) (Evans,

1987). Both definitions involve the concept of 'ore' discussed previously and tend to equate 'grade' with 'assay'. The grade of a body of rock is more than merely its average assay value and, it should be as much a qualitative term as it is quantitative (Mason, 1991).

Grade is assessed for an **orebody**. According to Taylor's (1991) ranking of terms (Table 6.1), the 'orebody' is a concept which lies above the natural break that separates it from the static concept of 'ore-rock'. It has a dynamic connotation which involves the economic factors of the mining process. The nature and properties of the minerals within the ore affect the process of mining and beneficiation which in turn determine whether the ore can be economically extracted.

The term 'grade' is used in various senses, depending on the particular stage of the mining process. This thesis deals mainly with the natural grade of the mineral deposit (mineralized body) and with a preliminary planning, cut-off grade that defines the ore body, which has an 'in situ ore grade' (Fig. 6.3).

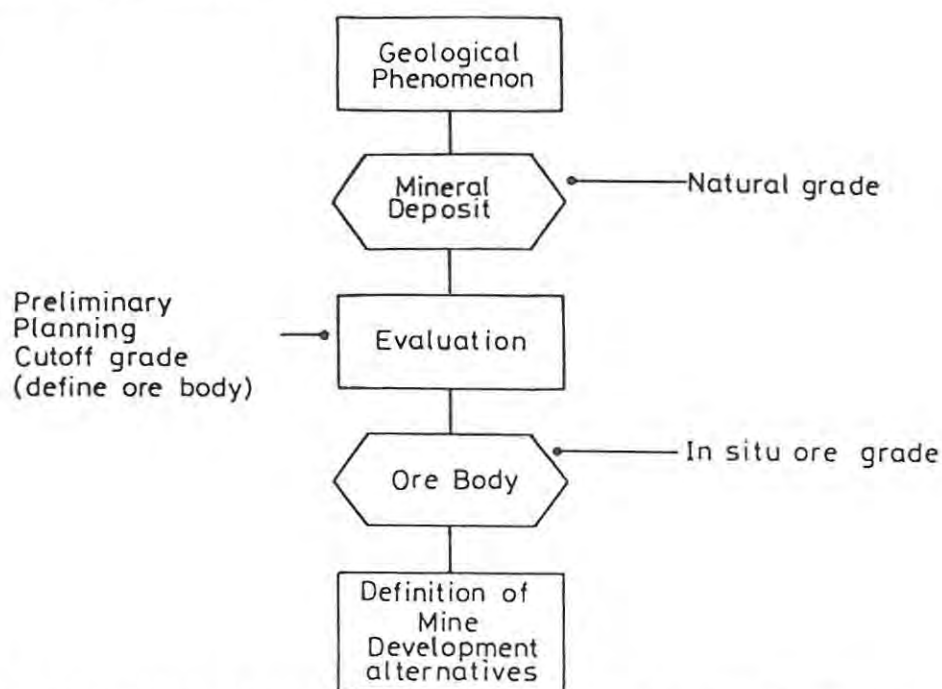


Fig 6.3 Schematic diagram depicting some of the senses in which grade is used through the first steps in the development of a mineral deposit (Modified from Esterhuizen, 1983).

Natural Grade

Natural grade is the term used for a mineral deposit. Mineral deposits are accumulations or concentrations of one or more useful substances that are for the most part sparsely distributed in the earth's outer crust (Jensen and Bateman, 1979). According to this definition, in the Thabazimbi district, the natural grade should be considered to be from the abnormal iron content of the banded iron-formations. Low grade resources of iron around the world have an estimated grade of between 20 and 47% of iron (Taylor et.al., 1988). Changes in demand and technology amongst others, may convert these resources into reserves (according to AIMM/ AMIC classification, Fig.6.1).

The main factors which affect the **natural grade** are related to the iron generation and deposition processes discussed in Chapter III.

Preliminary Planning Cut-off grade

A cut-off grade is any grade that for any specific reason is used to separate two courses of action; also it is any of a series of grades that is used to truncate a frequency distribution or to separate mineralized materials into graded fractions (Taylor, 1985).

During the exploration phase of a project, a cut-off grade is needed to define geographically and qualitatively the potential ore limits. The purpose is to make a fair prediction of the total amount of ore that may at some time be mined or treated. This cut-off is a 'planning' cut-off grade, determined by calculation or by comparison with analogous mining operations elsewhere. Planning cut-off grades are concerned generally with the total ore content, whereas 'operational' cut-offs are used mainly for available ore.

The Kwaggashoek East preliminary planning cut-off grade was determined by comparison with analogous mining operations developed in the Thabazimbi mine district. Two cut-off grades are used to separate the

mineralized material into different fractions: low grade ore and high grade ore. The low grade ore cut-off is 55% Fe and the high grade cut-off is 60% Fe. At the beginning of the exploration phase, a third cut-off grade of 50% Fe was considered for the low grade ore material. For this reason, this low grade material is included in the geological sections with the code LAE1 (see section K064, Fig. 3.3, Chapter III). Talc- and carbonate-hematite are also included in the inventory of the resources in the Thabazimbi district, but at a lower cut-off than that estimated for preliminary planning purposes.

Factors affecting the preliminary planning cut-off grade in many mine centres are generally out of the control of the geological department. These grades are established by a planning team at Headquarters, based on prices, costs, revenue and political factors, amongst others.

Price and ore specifications for the final product are considered to be the main factors affecting the variability of the preliminary planning cut-off grade. Both factors were analyzed in the previous chapter (Chapter V, Commodity analysis). An improvement in iron prices, in North American cents per Fe unit, has occurred during the past decade. Price forecasting is not easy because economists have not yet evolved a satisfactory theory of price fluctuations.

Ore specifications for the final product are closely related to technological and metallurgical developments which may result in variations in the iron grade and deleterious elements content.

In situ ore grade

The in situ ore grade is the grade quoted for the orebody above the planning cut-off and previous definition of a mining method. Because it is a grade within the ore body limits, the factors of modification are concerned with the processes responsible for the genesis of the ore body. The effectiveness of the secondary processes which led in the enrichment of the orebody is directly related to this grade.

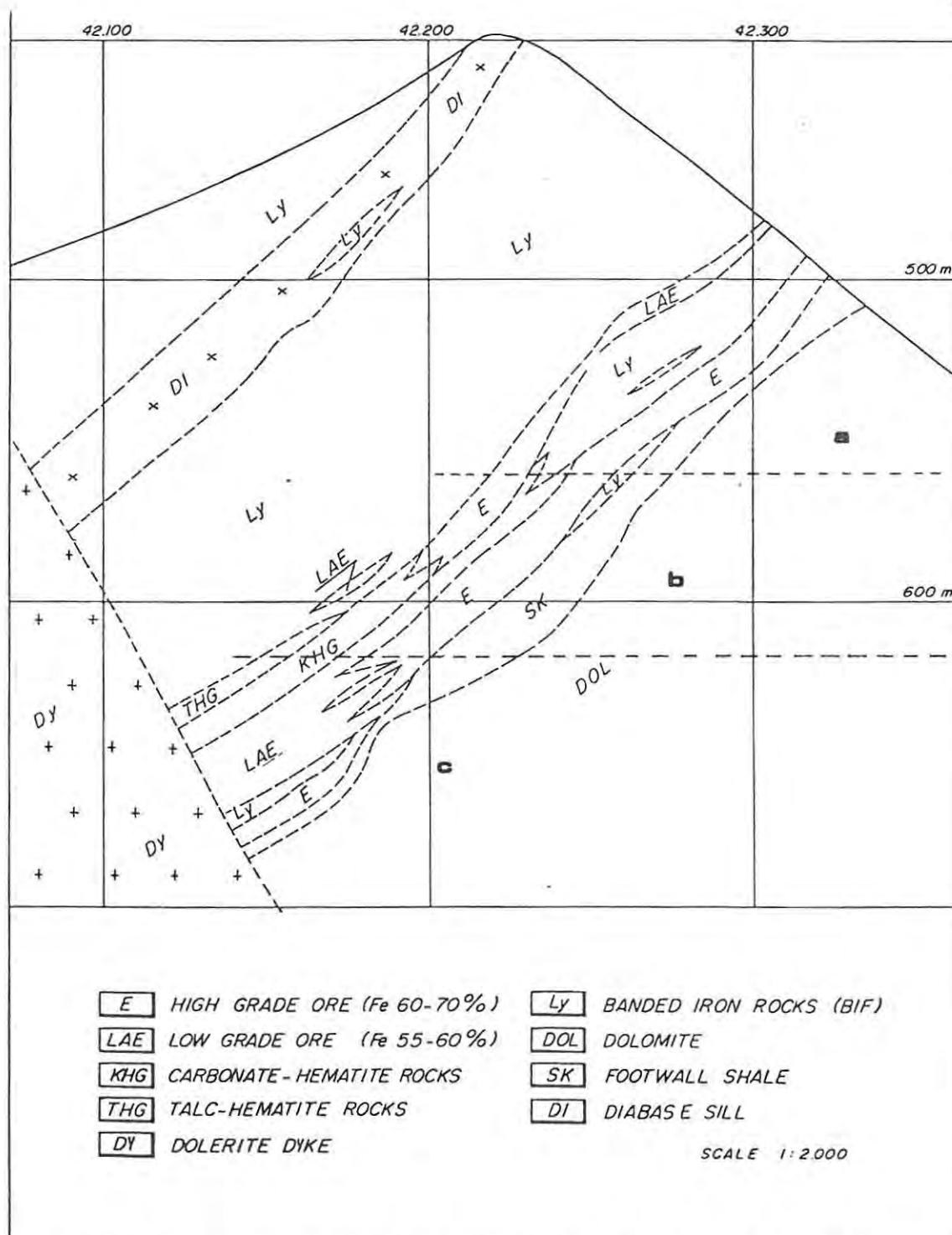


Fig. 6.4 Geological section of Kwaggashoek East showing three zones of in situ ore grade quality

- a) **Upper zone** with high grade soft ore including patches of banded iron formation and low phosphorus content.
- b) **Medium zone** with high grade ore and low grade ore subordinate, with textures laminated, brecciated and massive and low phosphorus content.
- c) **Low zone** with low grade ore, talc-hematite and carbonate-hematite types of rocks with laminated and brecciated textures and high phosphorous concentration.

The gradational hangingwall contact, the presence of banded iron formations within the ore body and the distribution of the deleterious elements are negative factors which influence the in situ ore grade. If we include the quality of the ore in the concept of grade, the ore textures should also be considered in the orebody model. In situ ore grade quality led to the identification of three main zones within the Kwaggashoek East ore body (Fig. 6.4): **a)** an upper zone, with high grade soft ore, including patches of banded iron formations and low phosphorus content located from surface to level - 560 m; **b)** a medium zone, between levels -560 and -620 m, with high grade ore and subordinate low grade with laminated, brecciated and massive textures, locally weathered and with low phosphorus content and **c)** a lower zone, below - 620 m, with low grade ore including high grade patches, with laminated and brecciated textures surrounding talc-hematite and calcite-hematite rocks. This third zone, in addition to its low grade of iron content has a very abnormal concentration of phosphorus (see Subsection 6.9).

6.6 Tonnage

Tonnage estimates are based on the volume and density of ore at a given grade. It is concerned with the shape (morphology) of the orebody, its dimensions, size and continuity. All these features are directly related to geological phenomena (Mason, 1991).

Tonnage affects planned rates of production and optimal plant capacity, thus influencing capital and operating costs in any potential mining development situation.

The morphology and size of the Thabazimbi orebodies are determined by a complex structural pattern. Duplication and, in places, triplication of the banded iron formation led to an increase in the total volume of the ore bodies in the district and therefore they are positive factors for tonnage purposes. The shape of the Kwaggashoek mineralized body is susceptible to be modified on its gradational hangingwall contact. This is defined on the basis of iron content, not being in a real geological

contact . The continuity of the orebody is affected by the presence of different rock types^{such} as talc-hematite and carbonate-hematite rocks and patches of iron formations.

The sharp foot-wall geological contact seems to be well delineated in the Kwaggashoek East deposit, although the spacing of the boreholes might not be sufficient to reflect all the small folds or faults, which could change the original tonnage estimate. This range of uncertainty was detected in some boreholes for which the Sperry Sun surveyed trace did not fit with the geological interpretation (e.g. borehole KW121, Section K078).

Volume estimation for in situ ore grade, divided into low grade (Fe>55%) and high grade (Fe>60%) was carried out according to two methods:

- a) linear cross section method. Sections drawn and planimetered at 50m along strike.
- b) computation of volumes in a three dimensional geological model, using LYNX software.

The difference between the results obtained by these two methods did not exceed 5%. This difference lies in the smoothness of the geological contacts and the bodies of adjacent sections in the 3D model in relation to the manual method (see Estimation methods, Subsection 6.7).

A third linear cross section method was applied to calculate tonnage for the different ore grade qualities in relation to iron and phosphorus content. In this method, the areas were calculated using graticulate paper. Tonnage for different ore types with their respective cut-off grades was calculated for this last manual method and a preliminary grade-tonnage curve was constructed in order to see the relationship between these parameters (Fig.6.7). Another grade tonnage curve (Fig.6.8) results from the calculation of different grade ore qualities in relation to phosphorus content (see Subsection 6.9).

Specific gravity

The specific gravity of a sample is almost as important as the metal assay. The average volume-per-ton factor for a mine as a whole does not necessarily apply to any of its individual blocks of ore and almost certainly not to every one of its samples (Dadson, 1968). Many measurements of specific gravity of different ore types have been conducted in the Thabazimbi district. Based on these results, values of 4.3 for high grade ore and 3.9 for low grade ore are used.

6.7 Estimation methods

Computation of reserves is recognized by the mineral industry as a distinct operation of increasing importance in the evaluation of mineral deposits in all stages of their development. Previously, valuation was based on facts, experience and intuition; methods have improved because our knowledge of mineral deposits, sampling and mining techniques has increased. The new concept of evaluation is a continuous action performed on a broader geological basis. The geological knowledge is used to simulate the possible deposit and to translate geological parameters into economic parameters.

The estimation method is one of the major components of a mineral reserve estimation (Bujtor and McMahon, 1983). Other components such as sampling, geology, mining factors, metallurgical and financial factors (Fig.6.5) may provide solid foundations, but all the work is spoiled if the estimation methodology is not properly applied and understood.

Whatever ore reserve methodology is used, it is extremely important to carefully document the method used and the limits applied. If the method is well documented, anyone using the reserve figures will have a fuller understanding of the confidence limits inherent in the stated reserves (Readdy et al., 1983). The major uncertainty in choosing a proper estimation method lies in the incorrect application of the method itself or a lack of understanding on the part of the estimator.

Selection of a method depends on the geology of the mineral deposit, the nature and density of the workings, the appraisal of geological and exploration data and the accuracy required. Time and the cost of computation are often also important considerations.

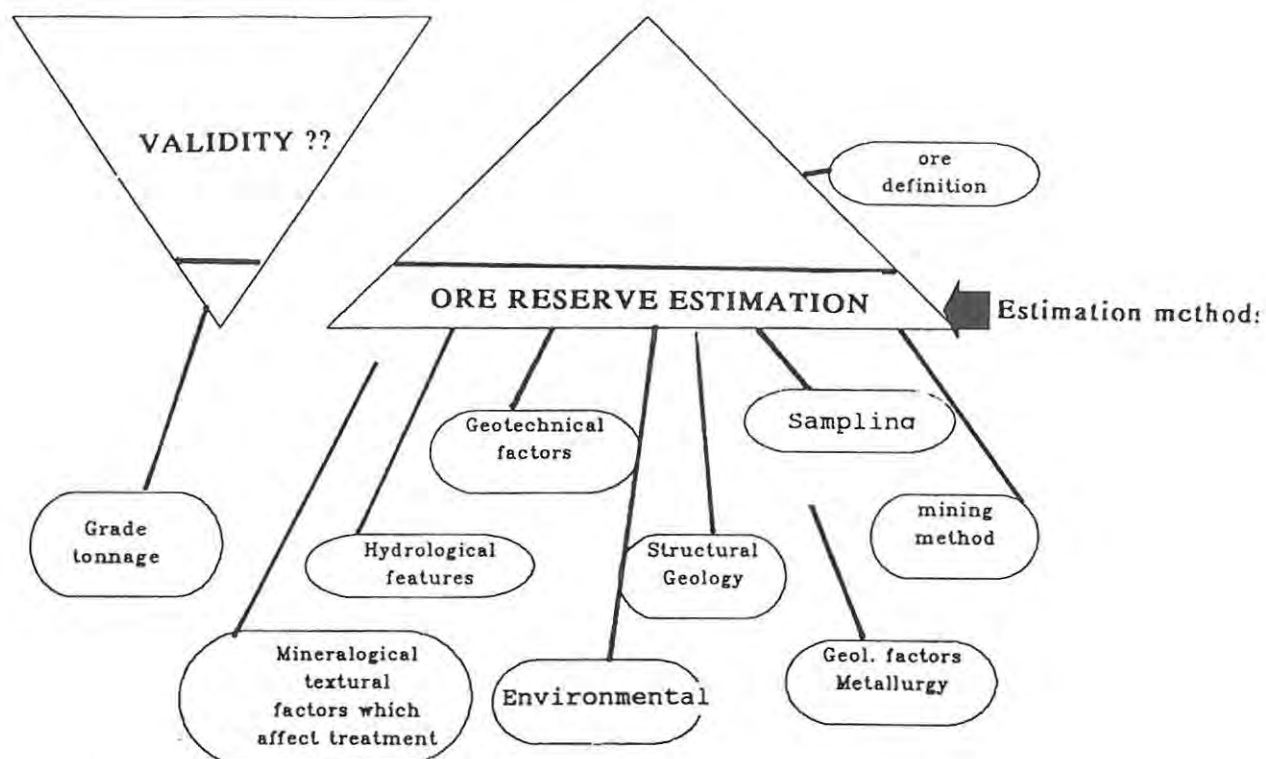


Fig. 6.5 Estimation methods as one of the major components of ore reserve estimation

Computations of reserves for a **bedded** deposit are less complex than for high grade, small volume, stock-type deposits with irregularly distributed values.

The 'classical methods' have stood the test of time but are now gradually being superseded by geostatistical techniques. They are, however, still applicable in many situations and may well produce, in some cases, an end-result superior to that possible using geostatistical methods.

Classical or traditional methods include calculation by sections, by polygons, triangulation, block matrices, contour methods and inverse distance weighting methods, amongst others. The tendency nowadays is to combine these methods with new computerised techniques. The computing hardware environment has changed radically during the 1980s, moving from mainframes to microcomputers for most applications. The computing software environment is also in transition. At one time, geologists wishing to do any serious computing had to be competent programmers. The spread of menu-driven, user-friendly programs on microcomputers has greatly increased the access of non-specialists to computing resources.

For many properties, the classical non-geostatistical methods are adequate, particularly in the early exploration stages. In fact, some authors (Readdy et al., 1982) suggest that even for those properties where the geostatistical approach is employed for reserve estimation, the geological and engineering staff should also prepare an estimate by traditional means. This will provide an internal audit for the reserves and, at the same time, require a continuing close appraisal of geological problems that influence the presently known geostatistically estimated reserves and production at the mine.

Geostatistical methods can only be satisfactory if sufficient sampling is available to allow for the production of a mathematical model which is adequate to describe the nature of the mineralization in the deposit under evaluation.

The reliability of reserve computations depends chiefly on the accuracy and completeness of our knowledge of the mineral deposit. It also depends on the accuracy of the **assumptions** accepted in order to interpret the variables, on the definitions of boundaries of the mineral bodies, on the accuracy of the samples taken and on the mathematical formulas employed.

Basic assumptions

Whatever method is used for reserve computation, several assumptions are taken for granted (Popoff, 1965): that

- * The basic elements of a mineral body observed or established at any specific position change or extend towards the adjoining area according to an appropriate principle for the interpretation of exploration data.
- * Observations are made in conformity with the **nature** of a given deposit and that the samples are taken with the **same precision** and are representative of a selected portion of the mineral body.
- * The mineral deposit has been explored by an **appropriate exploration method** and that the net of workings proves the **continuity** of the body. This hypothesis permits consideration of any element as having a constant value for a block, segment or the entire mineral body. Thus, the problem of computation is reduced to determining the volume of a block, segment or body by mathematical means.
- * For the purposes of computation, the true and often **complex form** of the mineral body can be represented with reasonable **accuracy** by a **hypothetical body** with a base surface lying in the plan or section.

The character of the mineral deposit, the required accuracy and the stage of development of the Kwaggashoek East deposit suggest the use of conventional methods. Conventional methods provide a good total or global estimate of ore body reserves. In the later stages of project development, it is suggested that a geostatistical study would provide a more reliable block-by-block estimation. An appropriate method for this kind of tabular deposit is the cross-section method. Three kinds of cross-section methods are distinguished according to the rules on which they are based (Popoff, 1965).

Cross-section methods

The initial step in the application of cross-section methods is to divide the mineral body into blocks by constructing geological sections at intervals along the transverse lines or at different levels conforming to exploration workings. The position and spacing of the sections depends to some extent on the purpose of computations and the nature of the deposit.

The cross-section methods have three modifications, depending on the manner of the block construction:

1. Standard method, based on the rule of gradual changes;
2. Linear method, based on the rule of nearest points;
3. Method of isolines, based on the rule of gradual changes.

In the standard cross-section method (Fig.6.6) the mean-area formula of a prism with base areas in parallel sections (e.g. areas of the same ore type) is the most common one; it is precise when there is no great difference in the size and shape of base areas. The construction of the 3D geological model of Kwaggashoek East was based on the same principles as the standard cross-section method. The connection between two similar ore types in adjacent sections was made by geological interpretation applying the gradual change rule. The use of this technique provides very smooth outlines of the mineralized body and the solid shape required to carry out further calculations.

The linear cross-section method (Fig. 6.6), based on the rule of nearest points, was applied as a secondary manual method in the Kwaggashoek East ore deposit. This method was also applied for the purpose of the phosphorus distribution in the present thesis (Subsection 6.9). The Kwaggashoek deposit was divided into twelve sections perpendicular to the strike of the ore body. The distance between sections is 50m. Each block was defined by a section and length equal to half the distance to the adjoining sections, in this case 25m.

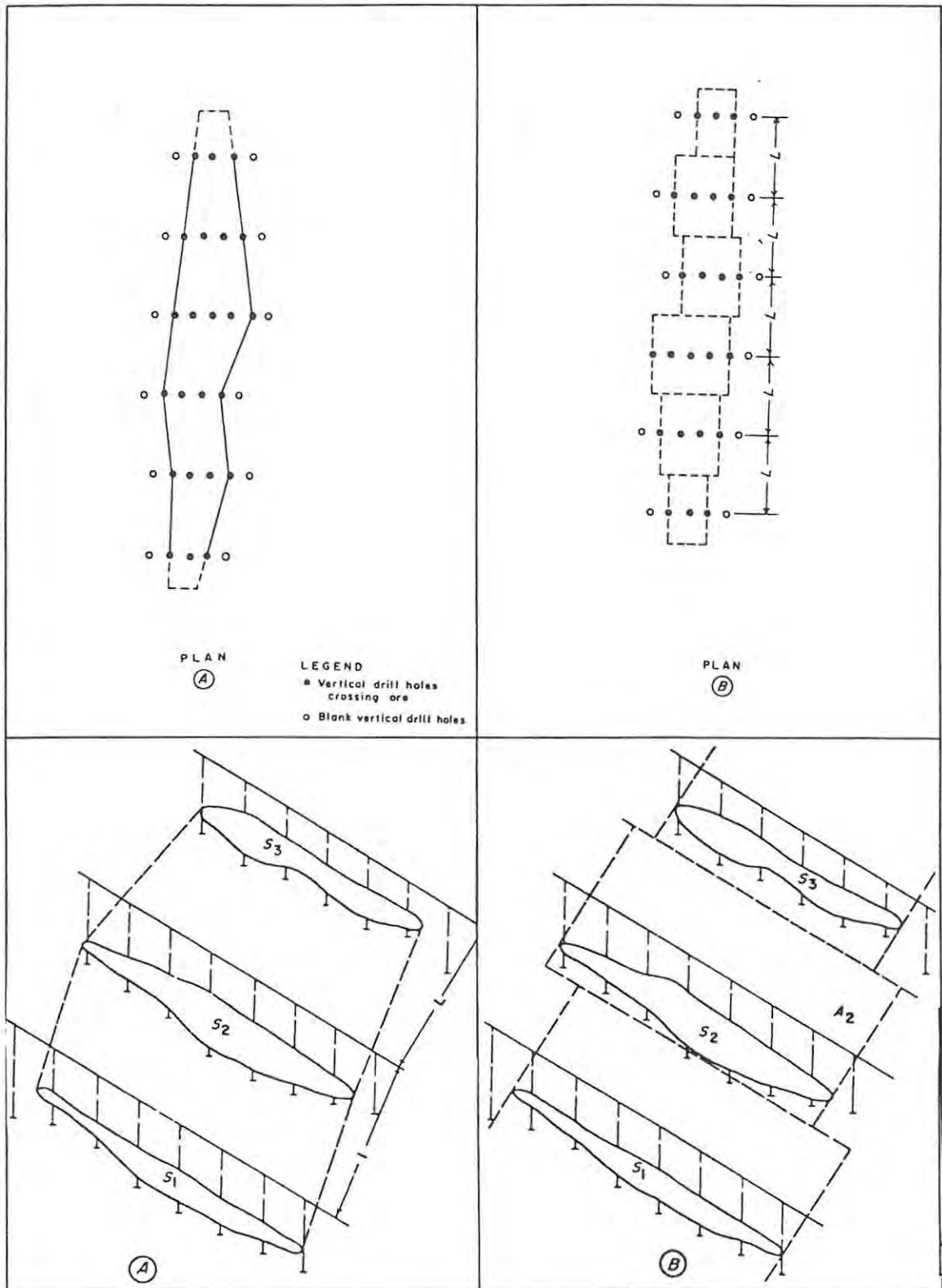


Fig. 6.6 Block Layout by Cross Section Methods
 A Standard cross section method based on the rule of gradual changes
 B Linear method based on the rule of nearest points
 (Modified from Popoff, 1965)

For accurate results, cross-section methods in a drilled exploration area require:

- a) that a sufficient number of boreholes be carried out completely crossing the mineral body and that an adequate number of observations and samples be taken from each section to represent the quality of the mineralized body.
- b) that the boreholes lie in or near the sections; and
- c) that all the boreholes are distributed more or less equally between the sections.

These three prerequisites are met by the Kwaggashoek East set of samples. The advantage of the cross-section methods is that they graphically portray the geology of the mineral deposit. The general procedure is simple and quick. To increase the accuracy of computations, the number of blocks should be as large as possible; in other words, the sections should be placed close together (Popoff, 1965). Well-defined and large bodies that are uniform in thickness and grade or have gradually changing values can generally be computed accurately by cross-section methods.

Finally all formulae for computing volumes, tonnages and average factors are approximate, due to the irregular size and shape of the mineral body, errors in substituting natural bodies by more simple geometric ones, geological interpretation, assumptions and inconsistency in the variables. The accuracy of the final result usually depends more on **geologic interpretation** and assumptions than on the method used.

Statistical methods

Classical statistical techniques are based on the assumptions that the samples are **independent** of each other (random) and that they are **representative** of the population analyzed. Samples collected from an ore deposit are seldom statistically independent of one another. This is a factor which is used to advantage in the calculation of geostatistical ore reserves in subsequent stages of the project development.

In the exploration stage of the Kwaggashoek East deposit the statistical methods were applied to compute the grade of the ore body assuming that the samples were representative of the population. The randomness of the samples is not adequate particularly in a vertical sense and in the high grade zones, where a good correlation between samples was detected (See Geostatistics).

'Statistics' and the statistical methods applied to geology fall into four categories (Cheeney, 1983):

- a) The lay person's idea of 'statistics', namely, data gathered for its own sake and presented in either graphical or tabular form as a **complete description** of a collection of objects.
- b) The calculation of numerical parameters from the original data used to **summarize** such a collection and to determine the nature of the sample population distribution.
- c) The application of statistics to test hypotheses, e.g. by comparison of the distribution of different populations.
- d) The estimation of the degree of confidence in the calculation of any experimental parameter.

The application of statistics in Kwaggashoek East ore reserve estimation was performed mainly in the categories 'b' and 'd' mentioned above. Histograms for different type of ore **grade** were constructed from the assay data base to determine the nature of the sample population distribution and to calculate normal statistical parameters. The confidence limits for high and low grade mean estimation were calculated.

The statistical analysis of the Kwaggashoek East database was done using the PC-XPLOR software version 1.2. (Appendices 6.5 and 6.6). The normal distribution of the sample values is not often satisfied except when the sampled mineralization has a relatively high grade, as is the case in this iron deposit (Rendu, 1981). If it can be assumed that the standard deviation of the samples provides a reasonable approximation of the

standard deviation for the entire deposit population, then this figure may be used to establish the precision of the grade estimate.

The standard deviation is used to establish the standard error of the mean, $S=s/\sqrt{N}$, where s is the sample standard deviation and N is the number of samples.

From a total of 1830 samples in the complete exploration area, 1083 samples lie in the low grade ($Fe > 55\%$) category (Appendix 6.5) and 787 samples in the high grade category ($Fe > 60\%$) (Appendix 6.6). The low grade population has been treated slightly differently than in the Thabazimbi mine district, considering all the samples above 55% Fe and not only within the range of 55% to 60% Fe. This was done in order to take into account the fact that there is no reason in the present conditions for the mining of only low grade parcels, while rejecting the patches of high grade ore within them. The following estimations were done for both populations:

For **low grade ore** ($Fe > 55\%$) a mean of 62.44% was computed for a total of 1083 samples (Appendix 6.5). The standard deviation of the population is 3.4, applying the formula for standard deviation of the mean,

$$S = s/\sqrt{N},$$

$$S = 3.4/\sqrt{1083} = 0.103$$

There is 68% probability that the true low grade ore lies within the range of 62.54% to 62.33% Fe.

For **high grade ore** ($Fe > 60\%$) a mean of 64.14% was calculated for a total of 787 samples (Appendix 6.6). The standard deviation of the population is 2.28. The standard deviation of the mean is:

$$S = 2.28/\sqrt{787} = 0.081$$

According to the normal distribution characteristics, there is a 68% probability that the true high grade lies within the range of 64.06% to 64.22%.

The category of **probable** given to the Kwaggashoek East ore reserves after its exploration phase, means that the margin of error associated with the ore definition is +/- 25% (Table 6.2). Applying this margin to the grade mean we have:

Confidence limits for $n > 25$

Central 75%, mean - $1.15s/\sqrt{N}$; mean + $1.15s/\sqrt{N}$

The factor 1.15 was extracted from a cumulative normal distribution table

Finally, for high grade ore:

$$p [(\text{mean} - 1.15 \cdot 0.081) \leq \mu \leq (\text{mean} + 1.15 \cdot 0.081)] = 75\%$$

$$p [63.21 \leq \mu \leq 65.07] = 75\%$$

and, for low grade ore:

$$p [(\text{mean} - 1.15 \cdot 0.103) \leq \mu \leq (\text{mean} + 1.15 \cdot 0.103)] = 75\%$$

$$p [62.32 \leq \mu \leq 62.55] = 75\%$$

Geostatistics

The primary purpose of any natural resource estimation method is to reliably estimate the overall ore reserves and the distribution of in situ and recoverable tonnages and grades throughout the deposit.

Conventional methods may provide a good total or global estimate of an ore body's reserves. However, a good geostatistical reserve study, paying careful attention to geological controls on mineralization, will provide not only a good total reserve estimate, but also a more reliable block-by-block reserve inventory with an indication of the relative confidence in the block grades estimated.

Geostatistical methods, like any others, cannot increase the quantity of basic sample information available, nor can they improve the quality or accuracy of the basic assay. Geostatistical methods can improve the **precision**, but not the **accuracy**, of the ore reserve estimation. The variance between a single observation or a computed average for an

element of a mineral body and its true value indicates the degree of accuracy or exactness of such an observation or estimate. An accurate measurement is free from all errors. Precision indicates only the degree of fluctuation in a certain suite of variables with respect to their proximity to each other (Popoff, 1965).

Unlike classical statistical approaches, geostatistics recognizes that the samples in an ore deposit should be spatially correlated with one another and that nearby samples will probably not be independent.

Variograms, representative of the mineralization of two representative zones were performed using the PC-XPLOR software version 1.2. The high grade zone, laminated, brecciated, with low phosphorus content (zone 'b' of insitu grade, Subsection 6.5 Fig 6.4) displayed a vertical relationship between iron samples that could be modelled by an appropriate "down the hole" semivariogram (Appendix 6.8.). A spherical semivariogram with a range of 8 m and a small nugget effect was modelled.

The low grade zone with high phosphorus content (zone 'c' of insitu grade, Subsection 6.5, Fig. 6.4) in the proximity to the dyke, displayed no correlation between samples, showing a very erratic behaviour of the mineralization (Appendix 6.8).

These results can have implications in relation with the ore genesis indicating that the supergene enrichment is a more uniform process. A comprehensive geostatistical ore reserve study was not warranted due to the wide spacing between the boreholes.

6.8 Grade-tonnage curve

A grade-tonnage curve was constructed taking into account a cut-off of 42% as a minimum, assuming dilution and no possibility of selective mining. This includes the intercalations of banded iron formations within the mineralized body and the low grade material from the hanging-wall contact. A tonnage of 100% was assigned to the real total tonnage

computed for the Kwaggashoek ore body. No real data were used in order to keep some information in the Kwaggashoek East database confidential.

The volumes for the tonnage computation were calculated by the linear method of cross-section. The areas of the different types of ore in each section were calculated manually with graticulate paper.

Table 6.4 Grade and tonnage values for different cut-off grades

% Tonnage	% Cut-off	Grade	n. samples
100	42	58.43	1547
94.46	45	59.45	1450
90.20	50	60.79	1302
83.78	55	62.44	1083
60.83	60	64.14	787

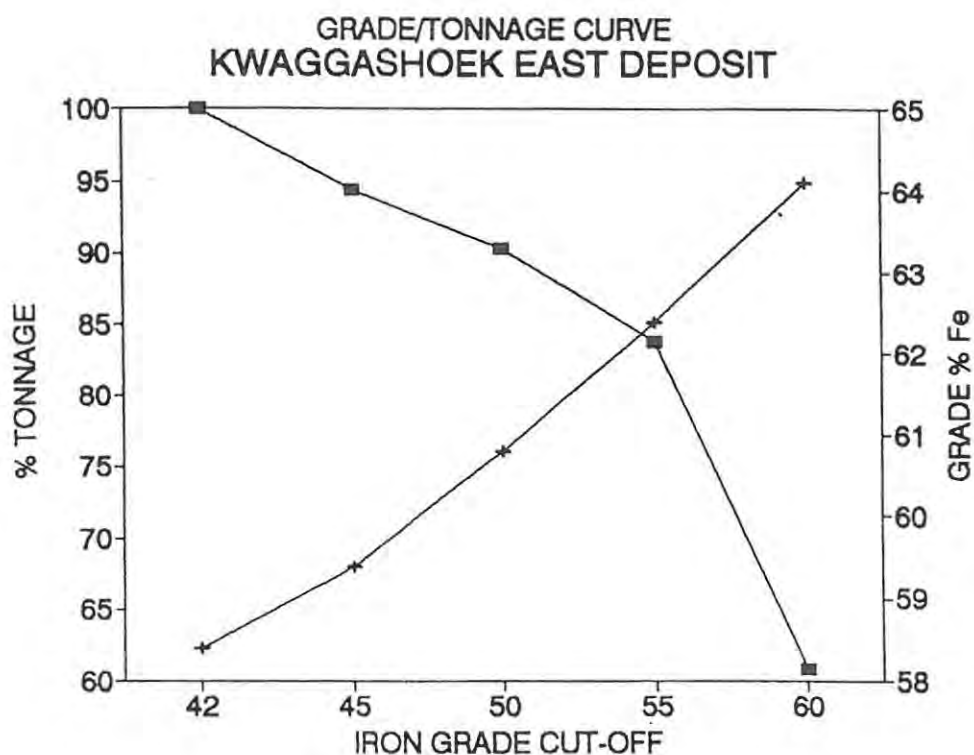


Fig. 6.7 Preliminary grade-tonnage curve for Kwaggashoek East deposit.

From the grade-tonnage curve (Fig. 6.7) it can be seen that the tonnage decreases steadily to a cut-off grade of 55%, at which nearly 85% of the total tonnage is available with an average grade of 62.44%. From this cut-off (55%) to the high grade cut-off (60%), the tonnage available drops to 60% of the total tonnage, with a mean grade of 64.14%. The optimization of grade and tonnage seems to be met with the actual cut-off grade used in the Thabazimbi mine district (55% for low grade ore).

Another grade-tonnage curve was constructed using ore quality as a cut-off (Fig. 6.8) in order to include some of the geological factors in the preliminary reserve estimation for this project. This curve is discussed in Subsection 6.9.

6.9 The negative impact of phosphorus in the Kwaggashoek East reserve estimation

The content and distribution of phosphorus within the mineralized body was chosen as an example to show the variability of the grade quality and its impact on the final ore reserve estimation. The same procedure is recommended for other factors which affect the mineability of the ore. Two crucial factors should be included in the geological model in more detail; they are: rock quality and structures. These factors were incomplete at the time of the first reserve estimation analyzed in this thesis.

Eleven geological sections were used to study the phosphorus content and its behaviour in the different lithological types. Seventy eight borehole traces were plotted, including analysis of the phosphorus content of 1450 individual samples as well as the lithological type (Appendix 7). From these analyses two main zones were distinguished within the ore body: a "**highfos**" zone close to the dyke and a "**lowfos**" zone in the middle of the orebody extending up to the surface. The phosphorus was divided in five different classes according to its statistical distribution:

P	≤	0.04 %
P		0.04 - 0.08 %
P		0.08 - 0.15%
P		0.15 - 0.20%
P		0.20 - 2.0 %

The highfos zone (Appendix 7) The bulk of the phosphorus values exceed 0.08%. The highfos zone is composed mainly of low grade ore, talc and calcite-hematite and high grade ore subordinate. Sinkholes and small folds are present throughout all the sections. This zone slightly overlaps zone 'c' of in situ grade (Fig. 6.4).

The lowfos zone (Appendix 7) is characterized by phosphorus values of less than 0.04% with few values in the P= 0.04 - 0.08% class. The lowfos zone is mainly composed of high grade ore, with low grade ore at the top and intercalations of banded iron formations. This zone is equivalent to zones 'a' and 'b' of in situ grade (Fig. 6.4). The areas, volume and tonnage for the different grade quality types in each zone were computed manually by the linear cross section method.

The grade quality types defined for computation purposes are:

ElowP	:	High grade ore (Fe > 60%) P< 0.08
LAE1P	:	Low grade ore (Fe > 55%-60%) low P content (P<0.08)
LAE11P	:	Low grade ore (Fe>50%-55%) low P content (P<0.08)
Ehfos	:	High grade ore (Fe >60%) high P content (P>0.08)
LAEhP	:	Low grade ore (Fe >55% - 60%) high P content (P>0.08)
LAE1hP	:	Low grade type 1 (Fe 50-55%) high P content (P>0.08)
KHhP	:	Calcite-hematite rock type with high P content (P>0.08)
THhP	:	Talc-hematite rock type with high P content (P>0.08)

The percentage tonnage for each of these units is represented in Table 6.5.

Table 6.5 Percentage tonnage for each grade quality type defined in relation to iron and phosphorus content.

	ElowP	LAElP	LAEl1P	Ehfos	LAElhP	LAElh1P	KHhp	THhP
Tonnage %	36.67	6.64	3.74	24.17	16.29	2.65	4.21	5.54

A grade-tonnage curve was constructed using these tonnages. The cut-off grade qualities of the X axis are explained in the legend of Figure 6.8. The mechanism of increasing the cut-off grade was done by sub-traction of the worse quality material to the best, in a progressive way from the mineralized body (A11).

The secondary Y axis shows the grade quality. In an attempt to measure qualitative terms a value of 100% was assigned to the best ore grade quality and 75% to the worst one. The increase in grade quality was calculated as follows:

- * An increment of 2.5% in grade quality was assigned when excluding carbonate and talc-hematite types.
- * An increment of 2.5% in grade quality was assigned when excluding high phosphorus types.
- * An increment of 2.25% in grade quality was assigned when excluding low grade type 1 (Fe < 55%).
- * An increment of 1.5% in grade quality was assigned when excluding low grade iron type (Fe , 55-60%).

A factor of influence (F) was assigned to the tonnage of each type of material excluded (see Table 6.5).

$$F = \% \text{ Tonnage} / 100 - \% \text{ELowP}$$

where % ElowP = 36.67% (from table 6.5)

in an approximation,

$$F = \% \text{ Tonnage}/64$$

The result of this procedure is shown in table 6.6

Table 6.6 Grade quality increase by progressive exclusions

	increment Fe related	increment P related	F	Grade qu
All				75%
-THhp	2.5 +	2.5 *	0.086	75.43%
-KHhp	2.5 +	2.5 *	0.065	75.76%
-LAE1hp	2.25 +	2.5 *	0.041	77.70%
-LAEhP	1.5 +	2.5 *	0.254	87.85%
-Ehfos		2.5 *	0.377	97.25%
-LAE11P	2.25	*	0.058	98.55%
-LAE1P	1.5	*	0.103	100.00%

Figure 6.8 is a graphic representation of the grade-quality/tonnage relationship based on these calculations.

The tonnage curve decreases slowly with the exclusion of the talc-hematite, carbonate-hematite and low-grade ore type 1 (Fe 50-55%) with high percentage of phosphorus (Fig. 6.8). A big drop in the tonnage is generated by the exclusion of low grade ore with high phosphorus content (LAEhP) where the available tonnage drops to 70%. Another drop is caused by the exclusion of high grade ore (Fe >60%) with high phosphorus content (Ehfos) from which the tonnage available is only 45%.

The grade quality curve shows a significative increase with the exclusion of the low grade type with high grade phosphorus (-LAE1hP and -LAEhP) which coincides with a big drop in tonnage. According to this curve, the optimum cut-off is 60% Fe for material with high phosphorus content and 55% Fe for material with low phosphorus.

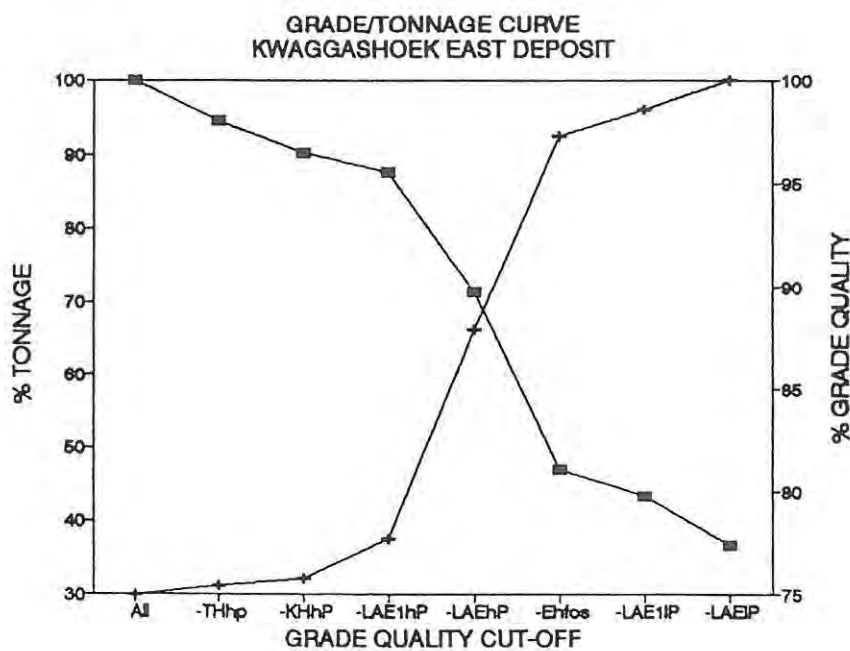


Fig. 6.8 Grade-tonnage curve for different grade-quality cut-off

ALL	:	Fe > 42% Talc-hematite, calcite-hematite low grade and high grade with low and high contents of phosphorus
-THhp	:	Total tonnage minus tonnage of the talc-hematite rocks with high of P content.
-KHhp	:	Subtotal (-THhp) minus tonnage of calcite-hematite rocks with high P content.
-LAE1hp	:	Subtotal (-KHhp) minus tonnage of low grade ore type 1 (Fe>50%) with high P content.
-LAEhp	:	Subtotal (-LAE1hp) minus tonnage of low grade ore (Fe>55%) with high P content.
-Ehfos	:	Subtotal (-LAEhp) minus tonnage of high grade ore (Fe>60%) with high P content.
-LAE1IP	:	Subtotal (-Ehfos) minus tonnage of low grade ore type 1 (Fe>50%) with low P content.
-LAE1P	:	Subtotal (-LAE1IP) minus tonnage of low grade ore (Fe>55%) with low P content.

The real impact of phosphorus on the in situ ore reserves is detected in the low iron grade types. This fact coincides with the hypothesis postulated for the phosphorus distribution within the mineralized body, associated to zones with an uncomplete supergene enrichment.

As it was mentioned before, the Kwaggashoek East deposit is part of a chain of deposits in the Thabazimbi mine district. This position affords the opportunity of blending material to the plant, even if the selectivity of the mining method is limited in each deposit. This flexibility allows the exploitation of low grade quality type of ores.

VII GENERAL CONCLUSIONS

From the **regional geology** overview of the Kwaggashoek East deposit it can be concluded that tectonics plays a probable indirect but important role in the genesis of the iron ore deposits of the Thabazimbi district:

* The tilting of the strata before the main period of supergene enrichment facilitated the migration and action of the percolating waters which led in the upgrading of the mineralized body.

* The Post-Karoo faults with their associated dykes acted as barriers for the underground waters increasing the effectiveness of the supergene process to the north-eastern sides of the dykes.

* The duplication and triplication of the Penge formation led to the multiple outcropping of the ore bodies facilitating the subsequent mining activities.

* Finally, the spatial relationship between the location of iron ore deposits and thrust faulting in many areas around the world suggests a certain genetic connection.

In the **local geological framework** the footwall shale is a key unit in: a) the genesis of the supergene enrichment, acting as a barrier for the percolating waters, b) the mining activities, helping in the minimization of dilution, and, c) the slope stability, where its sharp contact with the ore body is a negative factor.

Silica, aluminum, manganese and phosphorus are the most significant deleterious elements in Kwaggashek East deposit. A negative correlation between iron and silica led to a natural increase in quality grade with a concomitant decrease of this deleterious element in high grade ore. The aluminum and manganese distributions are such that they pose no contaminant difficulties in grade control.

The highest phosphorus concentrations within the mineralized body were related to depth, proximity to the dolerite dyke and small structures

interpreted as possible sinkholes. The P content is higher in talc-hematite, carbonate-hematite rocks and low grade ore. The relationship between high phosphorus content and low grade could be attributed to the incompleteness of the supergene process which leaves goethite as a remainder. Studies in the Hamersley iron ore in Australia support this hypothesis (Morris, 1986).

The **genetic model** of Kwaggashoek East deposit indicates that the deposit is the final product of more than one genetic process. The original source of iron appears to have been a very dilute hydrothermal input in the deep ocean waters (Klein and Beukes, 1989). The conduits for iron migration may have been zones of weakness that later have been reactivated leading to a very complex structural pattern. The primary iron deposition occurred as a result of changes in Eh/Ph conditions experienced by upwelling waters enriched in Fe^{2+} . The development of paleokarst activity in the underlying dolomites played an important role in generating brecciated textures which favoured the precipitation of secondary iron minerals during the supergene enrichment. The basal footwall shales and the dolerite dyke, as mentioned before, were fundamental barriers to percolating iron rich waters contributing to the effectiveness of the secondary enrichment.

From the general overview of the Kwaggashoek East geology, two kinds of **factors** may be distinguish: Positive factors which contribute to the upgrading of the mineralized body, and negative factors, which reduce ore grade or particularly quality of the ore, and thus reduce the potential ore reserves. A list of these factors is detailed in Section A conclusions (Chapter IV).

Geology is not an isolated science in the mining environment. The interrelationship between different disciplines calls for a team effort in economics studies. In this team, it is the geologists responsibility to define and describe the mineralized body as accurately and efficiently as possible and to perform any estimation on the broadest geological basis.

Ore reserves are subject to a wide spectrum of economic, metallurgical and mining conditions. Economic factors which are highly variable and beyond a mining enterprise's control affect the economic exploitation of a mineral resource. A good understanding of the economic issues inevitably requires a broad understanding of the forces which act on the markets for mineral products, in order to establish supply, demand and price conditions.

From the **commodity analysis** it can be concluded that supply-demand is expected to be balanced for the next five years. Despite the continued recession in the USA steel industry, Japan continues to be the largest market economy country steel maker and has signed agreements with its normal suppliers including South Africa. Prices are expected to improve slightly if suppliers from Eastern Europe continue to decline.

To hold mining costs at a minimum, open cast is virtually essential. The need to reappraise economic factors during the life of a mine in order to maximise the economic surplus and to minimise the wastage of natural, economic and human resources is continual.

The ore reserve estimation process is not a simple grade-tonnage calculation. Estimation is based on samples; they are the nerves of any mining operation. The adequacy and representativeness of samples is a vital foundation for ore reserve estimation. The good understanding of the terminology, the estimation method applied and a proper documentation of the whole procedure provides the required foundation for ore reserve reassessment.

The optimization of grade and tonnage in the Kwaggashoek East deposit seems to be met with the actual cut-off grade used in the Thabazimbi mine district (55% Fe for low grade ore). However the introduction of the grade-quality concept led to a decrease in tonnage. A complete geological model embracing all the parameters which can affect grade quality is suggested to have a final and reliable ore reserve estimate.

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APPENDIX 6.1

GEOLOGICAL CODES USED IN THE THABAZIMBI DISTRICT

Geol Code	Description	Geol Code	Description
ASH	Contend on asbest	KMT	Quartzite
BG	Blue-Grey	L	Percussion-drill
BL	Blocks	LAE	Low grade iron ore
BR	Breccie	LAM	Laminated
BRN	Brown	LI	Limonite
CAV	Calcite veins	LY	Bandend ironstone
CH	Chert	MAB	Macro-banded
CHN	Content of chert	MEB	Meso-banded
CHR	Chert-rich	MIB	Micro banded
CHL	Content of clorite	MS	Massive
CLR	Clorite-rich	MVW	± weathered
CR	Carbon-rich	O	Undif (texture)
DD	Discoidal	PNK	Pink
DI	Diabase	PO	Pulverized
DOL	Dolomite	PUC	Outcrop covered
E	Iron ore	RBB	Red brown
EVW	Slightly weathered	SEM	Cement
FEH	Ferruginized	SG	Steel-grey
FER	Iron rich	SIR	Chert-rich
G	Cave	SK	Shale
GB	Yellow-brown	SKH	Shaly
GBR	Brecciated	SKR	Shaly-rich
GG	Yellow-green	SO	Solid
GGR	Grey-green	SP	Specularite
GNI	Without information	SWG	Black-grey
GRN	Green	SWT	Black
GRS	Consistence like grit	TH	Minor content of talc
GRY	Grey	THG	talc-hematite
HOL	With cavities	TR	Talc-rich>15%
HVW	High weathered	TVW	totally weathered
IN	Intense cleavage	VKH	Filled up with cal-hem
KH	Calcitic	VLK	Filled with band iron
KHG	Calcite-hematite	VSK	Foot wall shale
KR	Calcite-rich	VTH	Filled up with talc-hem
KST	Limestone	WAD	Wad-(Mn)
		WIT	White

APPENDIX 6.2

MINERAL CLASSIFICATION THABAZIMBI

Column 1 **Grade and quality**

A	High grade ore (>60% Fe) P<0.035%, K ₂ O<0.09%
B	High grade ore with high P (>0.035% P)
C	High grade ore with high K ₂ O (>0.09% K ₂ O)
D	High grade ore with high P and K ₂ O (P>0.035%, K ₂ O>0.09%)
E	Low grade ore (55-59% Fe) (P<0.035%, K ₂ O < 0.09%)
F	Low grade ore with high P content. (P>0.035%)
G	Low grade ore with high K ₂ O content (K ₂ O>0.09%)
H	Low grade ore with high P and K ₂ O contents (P>0.035%, K ₂ O>0.09%)
X	Mineralized body Fe<55%
Y	Shale
Z	Diabase

Column 2 **Mineral class**

A	Martite - hematite (chert)
B	Martite - goethite (chert)
C	Martite - limonite (chert)
D	Martite - hematite (calcite) >8.4% CaO
E	Martite - hematite (talc) >4.78% MgO

APPENDIX 6.3

USBM/USGS Classification of Resources and Reserves

TOTAL RESOURCES

These include all minerals having present or future value and comprised of identified minerals together with those presumed to exist from geological evidence. Total resources consist of two components, i.e. reserves and resources as defined below.

RESOURCE

This is defined as a concentration of naturally occurring solid, liquid or gaseous materials in, or on, the Earth's crust in such a form that economic extraction of a commodity is currently or potentially feasible. Resources can be subdivided into two main groups, i.e. identified-subeconomic resources and undiscovered resources. These are shown in the summary diagram (Table appen. 6.3).

Identified-subeconomic resources are materials that cannot be classified as reserves but which may become so as a result of changes in the economic and legal environment. Paramarginal identified-subeconomic resources are those which are close to becoming economic at current metal prices or mining/processing costs or which are downgraded because of legal or political conditions. Submarginal identified-subeconomic resources require a substantially higher price, or a major cost reducing advance in technology, for their upgrading to the paramarginal or even into the reserve category.

Undiscovered resources are subdivided into hypothetical speculative resources. The former are undiscovered materials that might reasonably be expected to exist in a known mining district under known geological conditions. Speculative resources are undiscovered materials that may occur either in known types of deposits in a favourable geological setting where no discoveries have been made, or in as yet unknown types of deposits that remain to be recognized. In both cases, exploration that confirms their existence and reveals quantity and quality will permit their reclassification as reserves or identified subeconomic resources.

RESERVE

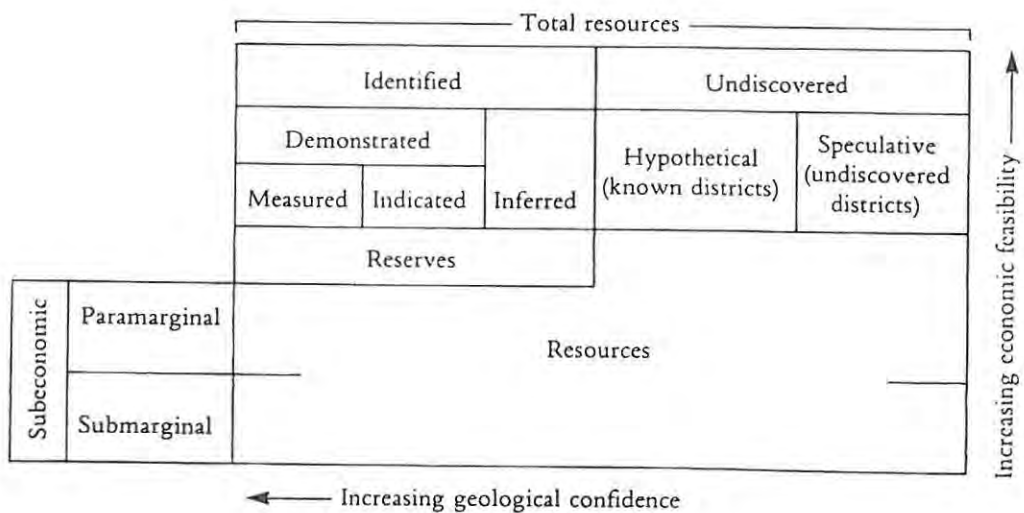
The following classification is taken verbatim from the USBM/USGS recommendation.

Measured ore (proved) is ore for which tonnage is computed from dimensions revealed in outcrops, trenches, workings and drill-holes and for which the grade is computed from the results of detailed sampling. The sites for inspection, sampling and measurement are so closely spaced and the geological character is so well defined that the size, shape and mineral content are well established. The computed tonnage and grade are judged to be accurate within limits which are stated, and no such limits is judged to differ from the computed tonnage or grade by more than 20%. Indicated ore (probable) is ore for which tonnage and grade are computed partly from specific measurements, samples or production data and partly

from projection for a reasonable distance on geological evidence. The sites available for inspection, measurement and sampling are too widely or otherwise inappropriately to outline the ore completely or to establish its grade throughout.

Inferred ore (possible) is ore for which quantitative estimates are based largely on broad knowledge of the geological character of the deposit and for which there are few, if any, samples or measurements. The estimates are based on an assumed continuity or repetitions for which there is geological evidence; this evidence may include comparison with deposits of similar type. Bodies that are completely concealed may be included if there is specific geological evidence of their presence. estimates of inferred ore should include a statement of the special limits within which the inferred ore may lie.

Table appendix 6.3 Summary diagram USBM/USGS classification



APPENDIX 6.4

AIMM/AMIC Classification of Resources and Reserves

RESOURCES

A resource is an *in situ* mineral occurrence quantified on the basis of geological data and a geological cut-off grade only. Categories recognized are as follows:

Inferred. This is an estimate, inferred from geoscientific evidence, drill-holes, underground openings, or other sampling procedures and before testing and sampling information is sufficient to allow a more reliable and systematic estimation.

Indicated. These are sampled by drill-holes, underground openings, or other sampling procedures at locations too widely spaced to ensure continuity but close enough to give a reasonable indication of continuity and where geoscientific data are known with a reasonable level of reliability.

Measured. These are intersected and tested by drill-holes, underground openings, or other sampling and procedures at locations which are spaced closely enough to confirm continuity and where geoscientific data are reliable known.

RESERVES

The term 'ore-reserve' means that part of a 'measured' or 'indicated' resource, which could be mined including dilution and from which valuable or useful minerals could be recovered economically under conditions realistically assumed at the time of reporting.

Probable. These reserves are stated in terms of mineable tonnes/volumes and grades where the conditions are such that ore will probably be confirmed but where the *in situ* identified resource has been categorized as; 'indicated' and has not been defined with the precision necessary for the 'measured' category. Probable ore-reserves include ore that has been sampled on a pattern too widely spaced to ensure continuity.

Proved. These are reserves stated in terms of mineable tonnes/volumes and grades in which the identified *in situ* resource has been defined in three dimension by excavation or drilling, and should include additional minor extensions beyond actual openings and drill-holes, where the geological factors that limit the orebody are known sufficient confidence, that it is categorized as a 'measured resource'.

CLASSICAL STATISTICS AND HISTOGRAMS

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 USER DESCRIPTION : fe in low grade

DATA VALUES ENTERED

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MINIMUM CUTOFF VALUE           : 55.000
MAXIMUM CUTOFF VALUE           : 69.420
TOTAL NUMBER OF SAMPLES USED   : 1083

MINIMUM HISTOGRAM VALUE        : 55.000
MAXIMUM HISTOGRAM VALUE        : 70.000
CLASS INTERVAL                  : .500

MINIMUM POPULATION DATA POINT : 55.000
MAXIMUM POPULATION DATA POINT : 69.420
TOTAL POPULATION                : 1083

```

UNGROUPED DATA GROUPED DAT

	UNGROUPED DATA	GROUPED DAT
TOTAL NO OF SAMPLES	1083	
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MEDIAN		62.755
GEOMETRIC MEAN	62.3524	62.389
NATURAL LOG MEAN	4.1328	4.133
STANDARD DEVIATION	3.4667	3.467
VARIANCE	12.0178	12.025
COEFFICIENT OF VARIATION	.0555	.055
MOMENT 1 ABOUT ARITHMETIC MEAN	.0000	.000
MOMENT 2 ABOUT ARITHMETIC MEAN	12.0178	12.025
MOMENT 3 ABOUT ARITHMETIC MEAN	-9.8292	-9.900
MOMENT 4 ABOUT ARITHMETIC MEAN	305.7410	305.390
MOMENT COEFFICIENT OF SKEWNESS	-.2359	-.237
MOMENT COEFFICIENT OF KURTOSIS	2.1169	2.111

NB. LOG MEANS CALCULATED ON SAMPLES ABOVE ZERO

*** KWAGGASHOEK EAST EXPLORATION IRON PROJECT BOREHOLES DATA ***
 *** THABAZIMBI MINE NORTHERN TRANSVAAL SOUTH AFRICA ***

CLASSICAL STATISTICS AND HISTOGRAMS

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 USER DESCRIPTION : fe in low grade

FREQUENCY DISTRIBUTIONS

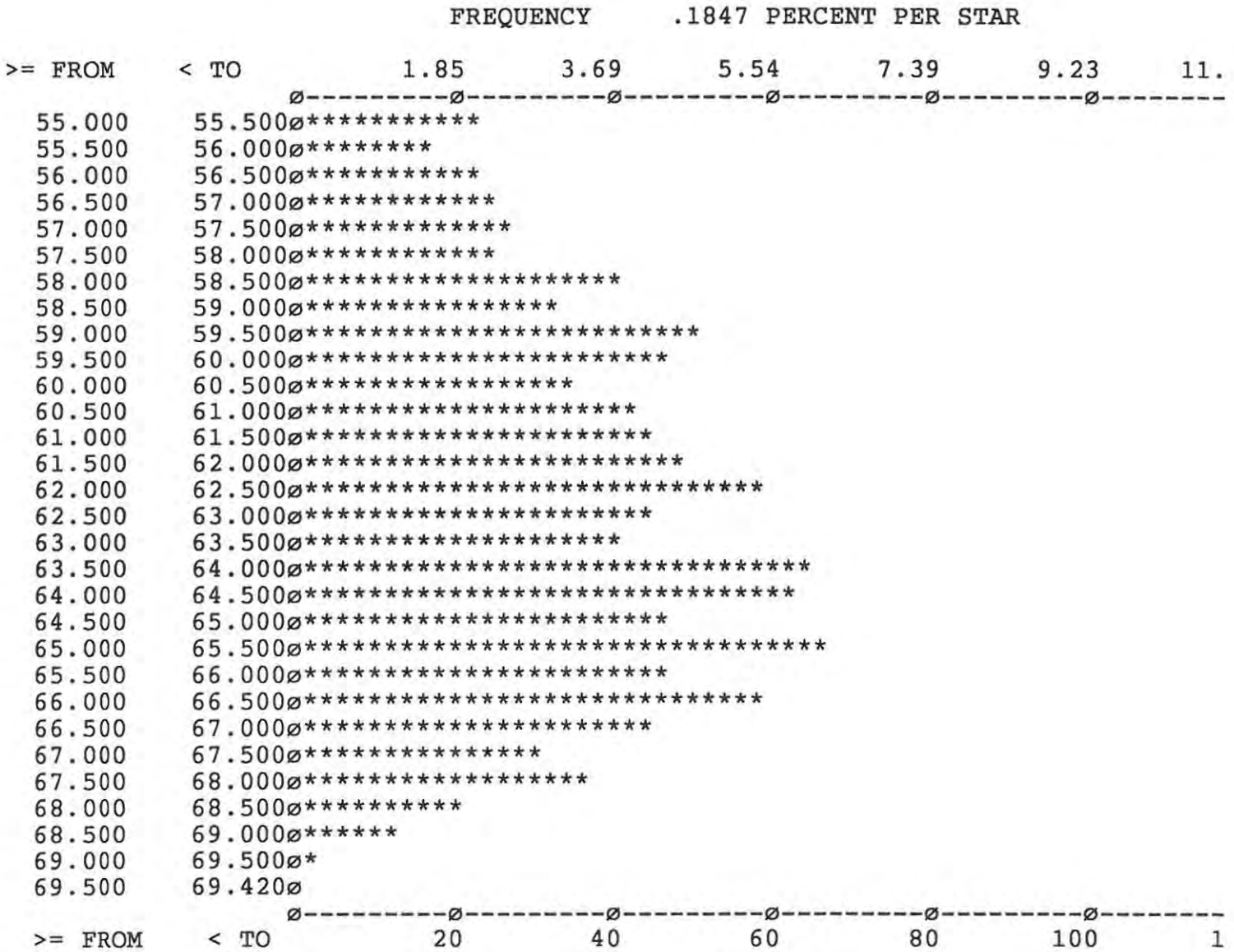
CLASS INTERVAL		<-- INCREMENTAL -->			< UPPER BND INCREASING			>= LOWER BND DECREASING	
>= FROM	< TO	COUNT	MEAN	CUM COUNT	CUM MEAN	CUM FREQ PERCENT	CUM COUNT	CUM MEAN	CUM FR PERCEN
55.000	55.500	22	55.216	22	55.216	2.03	1083	62.450	100.0
55.500	56.000	16	55.653	38	55.400	3.51	1061	62.600	97.9
56.000	56.500	21	56.190	59	55.681	5.45	1045	62.706	96.4
56.500	57.000	23	56.749	82	55.980	7.57	1024	62.840	94.5
57.000	57.500	25	57.221	107	56.270	9.88	1001	62.980	92.4
57.500	58.000	23	57.759	130	56.534	12.00	976	63.127	90.1
58.000	58.500	39	58.226	169	56.924	15.60	953	63.257	88.0
58.500	59.000	31	58.725	200	57.203	18.47	914	63.471	84.4
59.000	59.500	50	59.206	250	57.604	23.08	883	63.638	81.5
59.500	60.000	46	59.754	296	57.938	27.33	833	63.904	76.9
60.000	60.500	34	60.245	330	58.176	30.47	787	64.147	72.6
60.500	61.000	42	60.694	372	58.460	34.35	753	64.323	69.5
61.000	61.500	43	61.198	415	58.744	38.32	711	64.537	65.6
61.500	62.000	47	61.741	462	59.049	42.66	668	64.752	61.6
62.000	62.500	57	62.206	519	59.395	47.92	621	64.980	57.3
62.500	63.000	44	62.682	563	59.652	51.99	564	65.260	52.0
63.000	63.500	40	63.229	603	59.890	55.68	520	65.478	48.0
63.500	64.000	63	63.699	666	60.250	61.50	480	65.666	44.3
64.000	64.500	62	64.182	728	60.585	67.22	417	65.963	38.5
64.500	65.000	45	64.743	773	60.827	71.38	355	66.274	32.7
65.000	65.500	66	65.167	839	61.168	77.47	310	66.496	28.6
65.500	66.000	45	65.710	884	61.400	81.63	244	66.856	22.5
66.000	66.500	57	66.210	941	61.691	86.89	199	67.114	18.3
66.500	67.000	44	66.754	985	61.917	90.95	142	67.478	13.1
67.000	67.500	30	67.195	1015	62.073	93.72	98	67.803	9.0
67.500	68.000	35	67.755	1050	62.262	96.95	68	68.071	6.2
68.000	68.500	20	68.196	1070	62.373	98.80	33	68.406	3.0
68.500	69.000	11	68.641	1081	62.437	99.82	13	68.728	1.2
69.000	69.500	2	69.210	1083	62.450	100.00	2	69.210	.1
69.500	69.420	0	.000	1083	62.450	100.00	0	69.210	.0

NB : (GM) - GEOMETRIC MEAN

CLASSICAL STATISTICS AND HISTOGRAMS

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NORMAL HISTOGRAM



PC-XPLOR VERSION 1.20
 Exploration Data Manager
 By GEMCOM SERVICES INC.

GEMCOM SERVICES INC
 13:20:45 Serial no: 2000
 25/12/92 Page :

*** KWAGGASHOEK EAST EXPLORATION IRON PROJECT BOREHOLES DATA ***
 *** THABAZIMBI MINE NORTHERN TRANSVAAL SOUTH AFRICA ***

CLASSICAL STATISTICS AND HISTOGRAMS

EXTRACTION FILENAME : d:\kwagga\highfe
 DATA DESCRIPTION : Fe in high grade ore
 USER DESCRIPTION : Fe in High grade ore

DATA VALUES ENTERED

MINIMUM CUTOFF VALUE	:	60.000
MAXIMUM CUTOFF VALUE	:	69.420
TOTAL NUMBER OF SAMPLES USED	:	787
MINIMUM HISTOGRAM VALUE	:	60.000
MAXIMUM HISTOGRAM VALUE	:	70.000
CLASS INTERVAL	:	.500
MINIMUM POPULATION DATA POINT	:	60.000
MAXIMUM POPULATION DATA POINT	:	69.420
TOTAL POPULATION	:	787

UNGROUPED DATA GROUPED DAT

TOTAL NO OF SAMPLES	787	
ARITHMETIC MEAN	64.1465	64.187
MEDIAN		64.189
GEOMETRIC MEAN	64.1059	64.147
NATURAL LOG MEAN	4.1605	4.161
STANDARD DEVIATION	2.2846	2.280
VARIANCE	5.2196	5.199
COEFFICIENT OF VARIATION	.0356	.035
MOMENT 1 ABOUT ARITHMETIC MEAN	.0000	.000
MOMENT 2 ABOUT ARITHMETIC MEAN	5.2196	5.199
MOMENT 3 ABOUT ARITHMETIC MEAN	.6173	.571
MOMENT 4 ABOUT ARITHMETIC MEAN	59.9176	54.652
MOMENT COEFFICIENT OF SKEWNESS	.0518	.048
MOMENT COEFFICIENT OF KURTOSIS	2.1993	2.021

NB. LOG MEANS CALCULATED ON SAMPLES ABOVE ZERO

APPENDIX 6.6

Statistic analysis for high grade ore (Fe>60%) in Kwaggashoek East deposit.

*** KWAGGASHOEK EAST EXPLORATION IRON PROJECT BOREHOLES DATA ***
 *** THABAZIMBI MINE NORTHERN TRANSVAAL SOUTH AFRICA ***

CLASSICAL STATISTICS AND HISTOGRAMS

EXTRACTION FILENAME : d:\kwagga\highfe
 DATA DESCRIPTION : Fe in high grade ore
 USER DESCRIPTION : Fe in High grade ore

FREQUENCY DISTRIBUTIONS

CLASS INTERVAL		< UPPER BND					>= LOWER BND		
>= FROM < TO		<-INCREMENTAL->	INCREASING			DECREASING			
COUNT	MEAN	CUM COUNT	CUM MEAN	CUM PERCENT	FREQ	CUM COUNT	CUM MEAN	CUM PERCENT	
60.000	60.500	34	60.245	34	60.245	4.32	787	64.147	100.0
60.500	61.000	42	60.694	76	60.493	9.66	753	64.323	95.6
61.000	61.500	43	61.198	119	60.748	15.12	711	64.537	90.3
61.500	62.000	47	61.741	166	61.029	21.09	668	64.752	84.8
62.000	62.500	57	62.206	223	61.330	28.34	621	64.980	78.9
62.500	63.000	44	62.682	267	61.553	33.93	564	65.260	71.6
63.000	63.500	40	63.229	307	61.771	39.01	520	65.478	66.0
63.500	64.000	63	63.699	370	62.100	47.01	480	65.666	60.9
64.000	64.500	62	64.182	432	62.398	54.89	417	65.963	52.9
64.500	65.000	45	64.743	477	62.620	60.61	355	66.274	45.1
65.000	65.500	66	65.167	543	62.929	69.00	310	66.496	39.3
65.500	66.000	45	65.710	588	63.142	74.71	244	66.856	31.0
66.000	66.500	57	66.210	645	63.413	81.96	199	67.114	25.2
66.500	67.000	44	66.754	689	63.627	87.55	142	67.478	18.0
67.000	67.500	30	67.195	719	63.775	91.36	98	67.803	12.4
67.500	68.000	35	67.755	754	63.960	95.81	68	68.071	8.6
68.000	68.500	20	68.196	774	64.070	98.35	33	68.406	4.1
68.500	69.000	11	68.641	785	64.134	99.75	13	68.729	1.6
69.000	69.500	2	69.210	787	64.147	100.00	2	69.212	.2
69.500	69.420	0	.000	787	64.147	100.00	0	69.212	.0

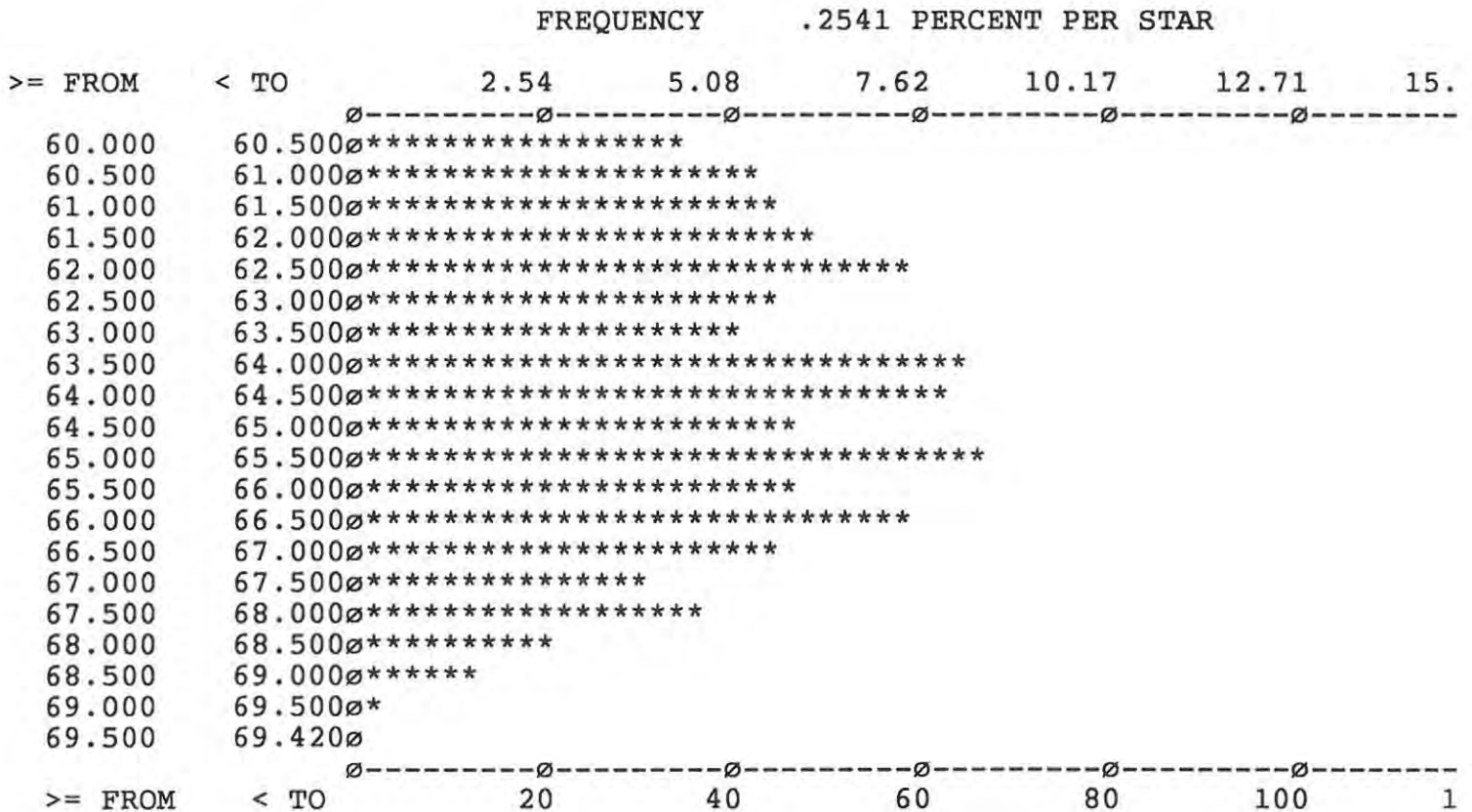
NB : (GM) - GEOMETRIC MEAN

*** KWAGGASHOEK EAST EXPLORATION IRON PROJECT BOREHOLES DATA ***
 *** THABAZIMBI MINE NORTHEN TRANSVAAL SOUTH AFRICA ***

CLASSICAL STATISTICS AND HISTOGRAMS

EXTRACTION FILENAME : d:\kwagga\highfe
 DATA DESCRIPTION : Fe in high grade ore
 USER DESCRIPTION : Fe in High grade ore

NORMAL HISTOGRAM



PC-XPLOR VERSION 1.20
Exploration Data Manager
By GEMCOM SERVICES INC.
*** KWAGGASHOEK EAST EXPLORATION IRON PROJECT BOREHOLES DATA ***
*** THABAZIMBI MINE NORTHERN TRANSVAAL SOUTH AFRICA ***

GEMCOM SERVICES INC

20: 9:22 Serial no: 2000

26/12/92 Page :

TITLE : DOWNHOLE VARIOGRAM
DESCRIPTION : kw 68-69
DATABASE USED : KWAGGA.G5A
TABLE USED : 5 ANALYSES
FIELD USED : FE
TRANSFORMATION : FE
NORMALIZATION : NONE

FILTER TABLE : 5 ANALYSES
FILTER FIELD : FE
UPPER BOUND : 70.000 LOWER BOUND : 50.000

1ST CLASS VALUE: .000
CLASS INTERVALS: 1.000 meters Å

SUMMARY STATISTICS

TOTAL NUMBER OF SAMPLES USED : 81
POPULATION MEAN : 64.907
STANDARD DEVIATION : 91.874
VARIANCE : 8440.877

TOTAL NUMBER OF SAMPLE PAIRS USED: 1431
AVERAGE DISTANCE APART : 12.440

APPENDIX 6.7

Down the hole semi variogram for high grade - lowfos, good quality ore.

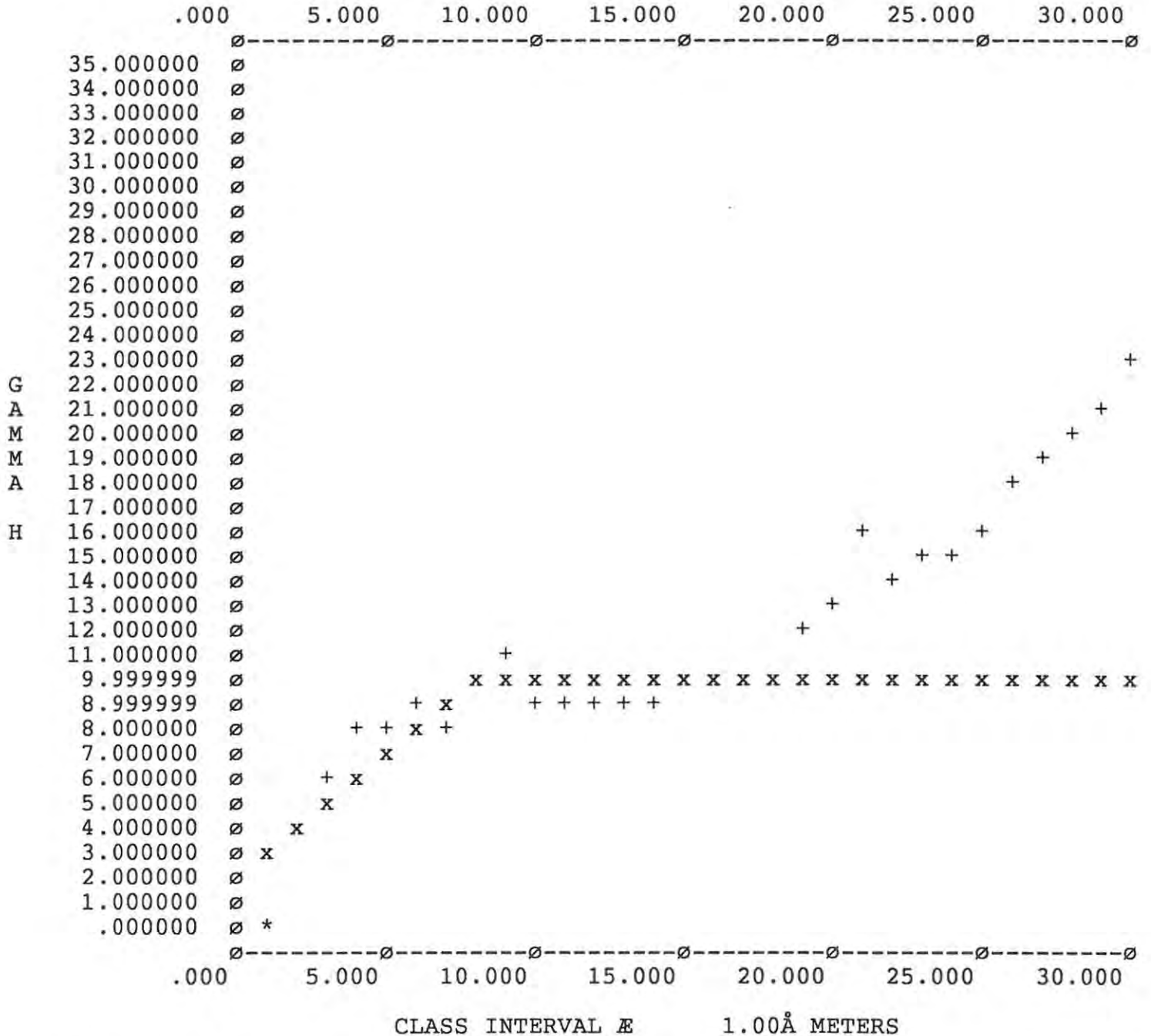
*** KWAGGASHOEK EAST EXPLORATION IRON PROJECT BOREHOLES DATA ***
 *** THABAZIMBI MINE NORTHEN TRANSVAAL SOUTH AFRICA ***

TITLE : DOWNHOLE VARIOGRAM
 DESCRIPTION : kw 68-69
 DATABASE USED : KWAGGA.G5A
 TABLE USED : 5 ANALYSES
 FIELD USED : FE

CLASS FROM	INTERVAL TO	SAMPLE USED	DRIFT	GAMMA(H)	LOCAL MEAN	AVERAGE DISTANCE
.00	1.00	0	.000000	.000000	.000000	.
1.00	2.00	76	.210000	3.797781	65.430000	1.
2.00	3.00	74	.109324	5.616368	65.379662	2.
3.00	4.00	72	-.357778	7.674504	65.404722	3.
4.00	5.00	69	-.305652	7.904967	65.417608	4.
5.00	6.00	66	-.555454	8.632160	65.545757	5.
6.00	7.00	64	-.351719	8.064909	65.498359	6.
7.00	8.00	62	-.397258	10.200643	65.575887	7.
8.00	9.00	60	-.354000	10.885018	65.628166	8.
9.00	10.00	59	-.260678	9.132429	65.396610	9.
10.00	11.00	57	-.128245	8.830226	65.481316	10.
11.00	12.00	56	-.314464	9.478646	65.288125	11.
12.00	13.00	55	-.375272	8.903637	65.149454	12.
13.00	14.00	54	-.498889	8.567128	64.994259	13.
14.00	15.00	52	-.671730	9.625723	65.032788	14.
15.00	16.00	51	-1.137451	10.455655	64.896568	15.
16.00	17.00	49	-1.265918	10.217684	64.870714	16.
17.00	18.00	47	-1.524042	10.334265	64.948191	17.
18.00	19.00	45	-1.766889	12.281629	65.003000	18.
19.00	20.00	43	-1.832558	12.910382	64.927209	19.
20.00	21.00	41	-2.161951	15.992128	64.995366	20.
21.00	22.00	39	-2.173589	13.940271	64.808333	21.
22.00	23.00	37	-2.097837	14.799825	64.688919	22.
23.00	24.00	35	-2.191142	14.862400	64.572714	23.
24.00	25.00	33	-2.132121	16.164629	64.518182	24.
25.00	26.00	31	-2.070967	17.698630	64.414194	25.
26.00	27.00	29	-2.154482	19.300940	64.310000	26.
27.00	28.00	27	-2.210000	20.298155	64.230555	27.
28.00	29.00	25	-2.447200	21.468905	64.106000	28.
29.00	30.00	23	-2.625217	23.445603	64.021739	29.

*** KWAGGASHOEK EAST EXPLORATION IRON PROJECT BOREHOLES DATA ***
 *** THABAZIMBI MINE NORTHERN TRANSVAAL SOUTH AFRICA ***

TITLE : DOWNHOLE VARIOGRAM
 DESCRIPTION : kw 68-69
 DATABASE USED : KWAGGA.G5A
 TABLE USED : 5 ANALYSES
 FIELD USED : FE



+ INDICATES EXPERIMENTAL SEMI-VARIOGRAM
 * INDICATES LESS THAN 1 THRESHOLD PAIRS IN CLASS
 x INDICATES SEMI-VARIOGRAM MODEL

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26/12/92 Page :

*** KWAGGASHOEK EAST EXPLORATION IRON PROJECT BOREHOLES DATA ***
*** THABAZIMBI MINE NORTHERN TRANSVAAL SOUTH AFRICA ***

TITLE : DOWNHOLE VARIOGRAM
DESCRIPTION : kw 68-69
DATABASE USED : KWAGGA.G5A
TABLE USED : 5 ANALYSES

MODEL 1

TYPE : NUGGET EFFECT
Co : 2.00

MODEL 2

TYPE : SPHERICAL
RANGE : 8.0
C : 8.00

PC-XPLOR VERSION 1.20
Exploration Data Manager
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GEMCOM SERVICES INC
20:48: 0 Serial no: 2000
26/12/92 Page :

*** KWAGGASHOEK EAST EXPLORATION IRON PROJECT BOREHOLES DATA ***
*** THABAZIMBI MINE NORTHERN TRANSVAAL SOUTH AFRICA ***

TITLE : DOWNHOLE VARIOGRAM
DESCRIPTION : kw 80 kw 63
DATABASE USED : KWAGGA.G5A
TABLE USED : 5 ANALYSES
FIELD USED : FE
TRANSFORMATION : FE
NORMALIZATION : NONE

FILTER TABLE : 5 ANALYSES
FILTER FIELD : FE
UPPER BOUND : 70.000 LOWER BOUND : 50.000

1ST CLASS VALUE: .000
CLASS INTERVALS: 1.000 meters Å

SUMMARY STATISTICS

TOTAL NUMBER OF SAMPLES USED : 62
POPULATION MEAN : 57.541
STANDARD DEVIATION : 81.460
VARIANCE : 6635.764

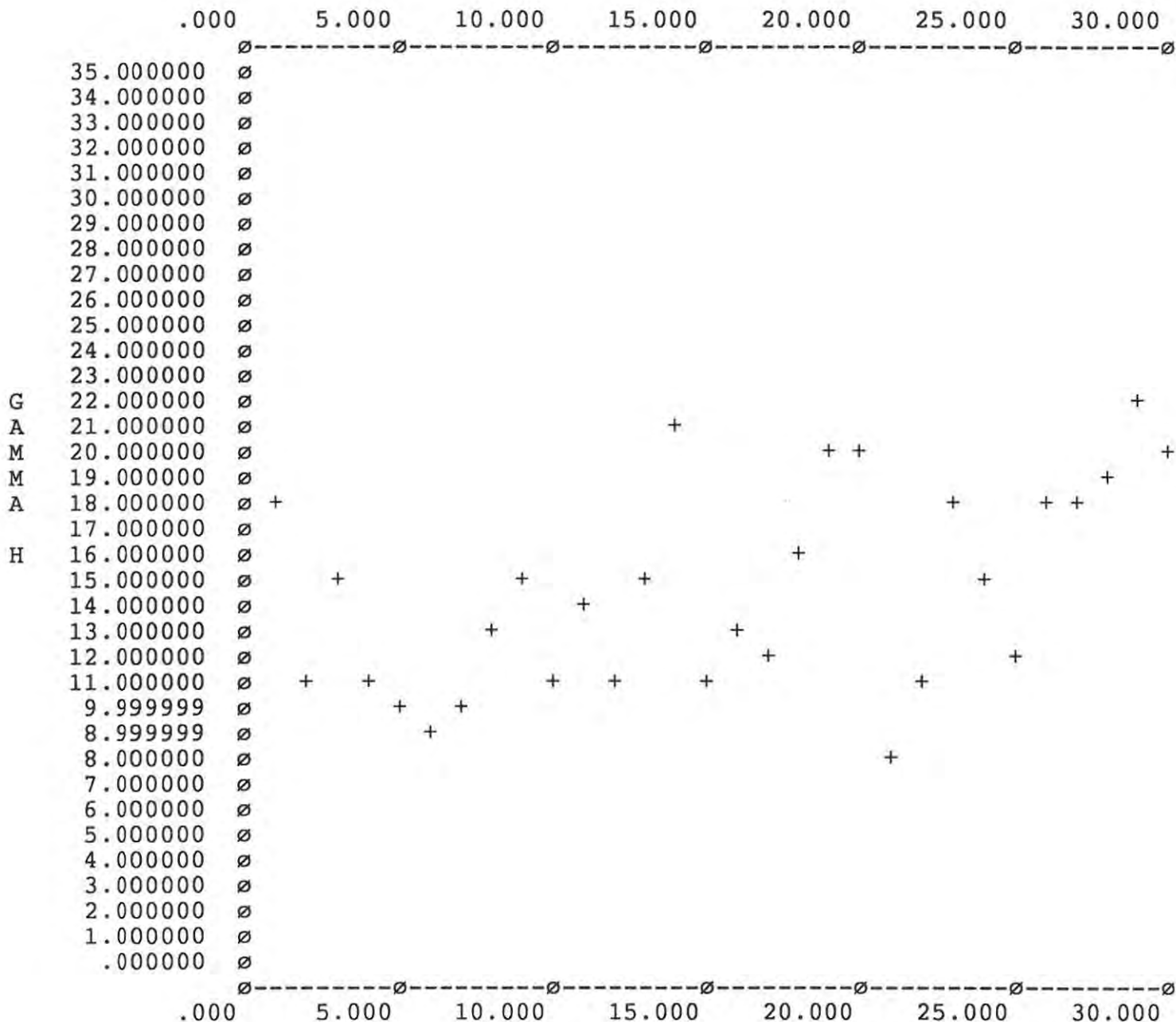
TOTAL NUMBER OF SAMPLE PAIRS USED: 878
AVERAGE DISTANCE APART : 11.672

TITLE : DOWNHOLE VARIOGRAM
 DESCRIPTION : kw 80 kw 63
 DATABASE USED : KWAGGA.G5A
 TABLE USED : 5 ANALYSES
 FIELD USED : FE

CLASS FROM	INTERVAL TO	SAMPLE USED	DRIFT	GAMMA(H)	LOCAL MEAN	AVERAGE DISTANCE
.00	1.00	2	5.600002	17.680013	59.700001	.
1.00	2.00	52	-.303077	11.203326	58.180385	1.
2.00	3.00	49	-.473469	14.667587	57.752245	2.
3.00	4.00	46	-.186956	11.444731	57.820870	3.
4.00	5.00	46	-.519565	10.260840	57.848044	4.
5.00	6.00	44	-.727272	9.439128	58.242273	5.
6.00	7.00	45	-.377777	10.158614	57.550222	6.
7.00	8.00	39	-.594872	13.499376	57.627180	7.
8.00	9.00	40	-1.462500	15.002768	57.230250	8.
9.00	10.00	37	-.929730	11.417719	57.639460	9.
10.00	11.00	38	-.798421	13.922205	57.519211	10.
11.00	12.00	37	-1.198378	11.244155	57.614324	11.
12.00	13.00	35	-.955429	14.600709	57.376571	12.
13.00	14.00	32	-2.035625	21.251936	57.494688	13.
14.00	15.00	33	-1.858788	11.239206	57.131212	14.
15.00	16.00	32	-.866875	12.694432	57.188438	15.
16.00	17.00	31	-1.461290	11.851130	57.237097	16.
17.00	18.00	29	-2.305517	15.533581	57.170000	17.
18.00	19.00	26	-2.315385	19.725771	57.234615	18.
19.00	20.00	25	-2.744000	19.501202	57.528000	19.
20.00	21.00	24	-2.225000	7.898751	57.120833	20.
21.00	22.00	21	-1.342857	11.015238	57.080953	21.
22.00	23.00	19	-2.784210	18.212370	57.292105	22.
23.00	24.00	18	-2.981111	15.366988	57.335000	23.
24.00	25.00	16	-3.206250	11.991563	57.340625	24.
25.00	26.00	14	-3.961428	18.142129	58.295000	25.
26.00	27.00	12	-2.558332	18.192914	57.479167	26.
27.00	28.00	11	-3.227272	19.377727	57.304546	27.
28.00	29.00	13	-5.400000	21.734618	57.446154	28.
29.00	30.00	12	-4.175000	19.573757	57.179167	29.

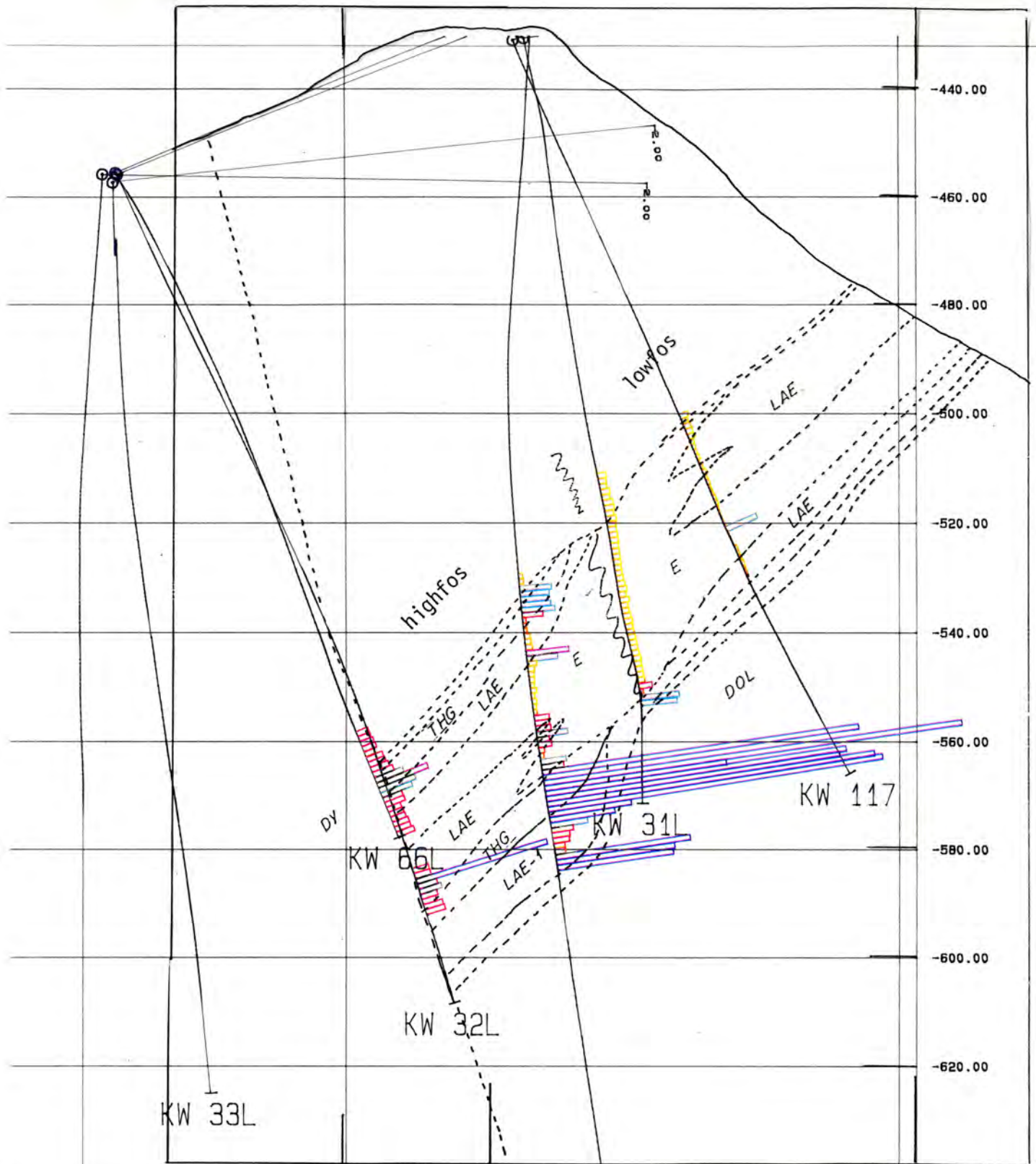
*** KWAGGASHOEK EAST EXPLORATION IRON PROJECT BOREHOLES DATA ***
 *** THABAZIMBI MINE NORTHERN TRANSVAAL SOUTH AFRICA ***

TITLE : DOWNHOLE VARIOGRAM
 DESCRIPTION : kw 80 kw 63
 DATABASE USED : KWAGGA.G5A
 TABLE USED : 5 ANALYSES
 FIELD USED : FE



CLASS INTERVAL \bar{x} 1.00Å METERS

+ INDICATES EXPERIMENTAL SEMI-VARIOGRAM
 * INDICATES LESS THAN 1 THRESHOLD PAIRS IN CLASS
 x INDICATES SEMI-VARIOGRAM MODEL



Appendix 7

Geological section of Kwaggashoek East deposit showing phosphorus content plotted down the borehole trace depicting highfos and lowfos areas. Section K0 64, Geological units detailed in Fig. 3.4

PCXPLOD, VERSION 1.20

KWAGGASHOEK EAST

	P < .04		.04-.08
	.08-.15		.15-.20
	.20-2.0		

12/ 8/1991 SCALE 1: 1000

KW 67L

